

AUDITORY RHYTHMICITY ENHANCES MOVEMENT AND SPEECH MOTOR CONTROL IN PATIENTS WITH PARKINSON'S DISEASE

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INTRODUCTION

The study of music as a complex sensory pattern involving cognitive, sensorimotor and affective processes in the human nervous system has received increasing attention in behavioral and brain research in the last decade. The high performance-processing features of music, its complex perceptual demands, the interplay between intrinsic talent and capacity to learn, and its strong and universal emotional functions have made it a fascinating and intricate, yet very useful, model for studying brain functions with reference, for example, to cog-

nitive learning, cortical plasticity, pattern perception, temporal processing in the human nervous system, motor control, and emotional response. A special role in the study of music perception must be given to rhythm as the most essential structural and organizational element of music. Thus, attention is being focused increasingly on the role of rhythm in cognitive functions such as attention and memory, as well as in motor performance and learning, within the study both of music and of behavior and brain function outside the musical sphere.

We have been studying the effect of auditory rhythm on motor performance, in musi-

cians and in rehabilitative contexts, for the past 10 years. The results in various patient groups – enhancement of motor functions through rhythmic stimulation and rhythmic organization of motor training – have been very encouraging. Our rhythmic motor research has focused in particular on enhancing movement functions in patients with Parkinson's disease (PD). Since dysfunctions of the basal ganglia have frequently been associated with disturbances in temporal aspects of motor control, the application of auditory rhythm with its implicit timing functions (in perception and action) have opened up important avenues of study with regard to the effect of sensory timekeepers on impaired internal timing mechanisms. In the following pages we: a) summarize the results of several research studies on rhythmic facilitation in PD, b) discuss potential mechanisms of interaction between auditory rhythmicity and the human motor system, and c) present the results of a new study applying rhythmic cueing to speech intelligibility in hypokinetic dysarthric speakers with PD.

RHYTHMIC AUDITORY STIMULATION IN GAIT TRAINING: RESULTS OF STUDIES

In an initial entrainment study we compared rhythmic auditory-motor facilitation, through an external auditory cue, of gait patterns in PD patients on dopaminergic medication ($n=21$), off medication ($n=10$), and 10 age-matched healthy elderly persons (1). The Parkinsonian patients showed slightly higher variability in synchronization measures compared to the healthy controls, with unmedicated patients performing slightly worse than medicated ones. However, close frequency entrainment to the rhythmic cue remained intact in most patients indicating the functional integrity of auditory rhythmic entrainment mechanisms even in the presence of basal ganglia dysfunction. Faster rhythms produced statistically sig-

nificant improvements in velocity, stride length, and cadence, which were retained in a trial without rhythmic cueing that immediately followed the cued trials.

The demonstrated ability of PD patients to access and couple their gait patterns to rhythmic sensory cues led to a 3-week training study with rhythmic auditory stimulation (RAS). Study participants were randomly assigned to 3 experimental groups: a) daily 30-minute gait training with RAS; b) daily 30-minute gait training of the same intensity but without rhythmic facilitation; c) no training. Pre- and post-testing, which included flat surface walking and walking on a slope, was carried out without rhythmic cueing. RAS training was accomplished with music, recorded onto audio tapes. Using a synthesizer/sequencer, this music was specially composed with precise beat frequencies in order to create the desired training tempos for each patient. Significant improvements in gait parameters pre- and post-testing and between groups emerged only in the RAS-trained group (2), in which velocity increased by 25%, stride length by 12%, and step cadence by 10%. Once the post-test trials had been completed, the patients were asked to reproduce from memory the walking speed corresponding to the rhythm of the last training tape they had heard the day before post-testing. Contrary to previous findings that time estimation and time recall is impaired in PD patients, the error in gait tempo reproduction after rhythmic-musical RAS training was only 5%.

Muscle activation (EMG) patterns of parkinsonian and healthy subjects were studied by our research group, analyzing variability and bilateral symmetry of the gastrocnemius, tibialis anterior, and vastus lateralis muscles (3). EMG components reflecting shape and timing of muscle activation patterns were computed using the magnitude and phase of the cross-correlation function between individual stride profiles and the latency corrected ensemble average (LCEA) for variability, and be-

tween bilateral LCEAs for symmetry. Parkinsonian gait resulted in increased shape variability and asymmetry in EMG patterns for the gastrocnemius and anterior tibialis muscles, and reduced timing variability in the gastrocnemius muscle compared to the patterns found in healthy elderly subjects. After 3 weeks of RAS-training, the EMG parameters had shifted towards healthy elderly values in the measures where population differences had previously been found. Tibialis anterior shape variability and asymmetry and gastrocnemius shape variability had decreased significantly while timing variability in the gastrocnemius muscle had increased and bilateral asymmetry in the gastrocnemius was reduced. Thus, in addition to the expected decreases in asymmetry and shape variability towards healthy elderly parameters, we simultaneously observed increased timing (onset/offset) variability, which may reflect greater functional adaptability in the muscle drive during stable locomotion.

Finally, to investigate the long-term effects of RAS on gait ability in patients with PD, we followed up 25 patients after an initial training period of 3 weeks, re-testing them weekly for 5 weeks after training had ended and during which no further physical exercise or gait training was initiated (4). RAS-training protocols followed a 'stepwise limit cycle entrainment' (SLICE) program in which the frequencies of the rhythmic cue were set initially to the patients' natural frequencies and then incremental tempo changes were implemented to gradually entrain new optimal gait frequencies. The optimization of step cycle durations was followed by comprehensive spatiotemporal improvements in the stability of gait kinematics. After an improvement of about 18% in gait velocity after 3 weeks of training, the improved gait parameters were retained for 3 weeks. At week 4, follow-up testing showed a first decline of about 10%, and at week 5 gait performance had declined almost to pre-test values. The training improved stride length more than ca-

dence, although comparison of the decline slopes showed that stride length also declined at a greater percentage rate than cadence over the 5-week follow-up period.

AUDITORY-MOTOR MECHANISMS

We are only just beginning to understand the exact neuroanatomical and neurophysiological basis of the interactions between the motor system and the auditory system in the human brain. However, several findings, some of them very recent, are already helpful in efforts to conceptualize the role of rhythm in motor control. From basic sensory physiology we know that the auditory system is a very fast sensory processing system, faster than other sensory systems such as the visual system, and very sensitive to temporal information processing. The powerful capacity of the auditory system to detect temporal patterns of periodicity and structure in acoustic information, an evolutionary necessity for meaningful acoustic information processing (as in speech for example), makes the auditory system an excellent system to neurally compute and code rhythmicity in sensory signal processing.

Less is known at the present time about the apparent link between auditory processing and motor control circuits. From a behavioral and cultural point of view, even the most cursory look at music anthropology, with its multitude of examples of the centrality, in human life, of physical responses to music, e.g., in dance, religious rituals, education and work, soon reveals the strong effect of sound on movement. Some basic physiological data have provided evidence of an auditory-motor pathway by which, via reticulospinal connections, sound exerts a priming and timing effect on spinal motor neuron activity (5). We have shown in several psychophysical synchronization studies how accurately and quickly auditory rhythm entrains motor responses even below

thresholds of conscious perception (6). Preliminary evidence of neural correlates of rhythmic processing in the brain via magnetoencephalographic (MEG) recordings suggests (7) that correlates of precise frequency coding are manifested in the magnitude of the auditory field potential (M100) in the primary auditory cortex. Neuroanatomical correlates in brain imaging (PET) show involvement of parietotemporal-thalamic circuits and cerebellar involvement. However, it is unclear at this point whether specific neural structures are responsible for rhythmic motor synchronization or whether neural excitation patterns in the auditory system are directly projected via spatiotemporal transformations into motor system circuits (7).

One of the most useful modeling approaches of rhythmic auditory-motor synchronization is based on entrainment theory and uses system features of coupled nonlinear oscillators. The physiological attractor function of auditory rhythm as an external *zeitgeber* on motor responses can be used to entrain movement into optimal limit cycles, which will result in enhanced stability of the temporal, spatial and force parameters of movement kinematics. The way rhythm enhances movement during entrainment can be shown in a continuous time reference model (CTR) in which rhythm provides enhanced time information to the motor system throughout the entire movement cycle rather than only at the beat events which mark interval durations. In support of the CTR model, recent evidence has shown that movement synchronization to an external rhythm indeed involves duration or frequency entrainment and not only event or phase entrainment (8). Using enhanced precision as a criterion for optimization modeling in motor control, it follows quite logically that enhanced timekeeper information will improve spatiotemporal and force-dynamic movement organization and coordination when internal temporal control is impaired due to injury or disease (9). The clinical benefits of

these mechanisms are clearly visible in studies which apply rhythmic stimulation and rhythmic patterning to rehabilitative motor learning. In PD, intact basal ganglia functions do not appear to be necessary in order to access rhythmic auditory facilitation. We may conclude that the auditory input operates through two mechanisms in PD. First, rhythmic cueing enhances temporal precision in motor planning and implementation which, based on optimization principles in motor control, will enhance accuracy in the control of space and force dynamics of the entire movement pattern (10). Second, sequencing of movement through rhythmic sensory input, possibly affects faulty pallidal-SMA circuitry, serving as a 'priming' and 'trigger' function to reduce akinesia and bradykinesia (11).

THE EFFECT OF RATE AND RHYTHM ON ENHANCEMENT OF SPEECH INTELLIGIBILITY IN HYPOKINETIC DYSARTHIC SPEAKERS WITH PARKINSON'S DISEASE

The purpose of this study was to investigate the effectiveness of different rhythm and rate components of speech modification techniques in hypokinetic dysarthric speakers with PD. Reduction of speech rate has been reported to increase intelligibility in dysarthric speakers (12-14). Rate modification is widely used to improve speech intelligibility in dysarthric patients, and there are actually several different strategies used to implement rate change. One involves the application of rhythmic cues, which can be used as pacesetters. For example, when patients are instructed to speak at an assigned rate, the target rate is provided in the context of a specific rhythmic beat frequency. The rhythm may be presented as a metered rhythm, following an isochronous metronome-like pattern, or it may involve a patterned rhythm, which follows closely the inflection patterns of natural speech. In other words, ther-

apeutic adjustments of speech rate are implemented using any one of several possible pacesetters. However, with the primary objective of altering a patient's habitual rate of speech, clinical practitioners typically establish optimal rate settings, without paying attention to their concomitant selections of underlying rhythmicity.

Although few studies have examined the particular effects of rhythmicity on speech techniques, Duffy (15) suggests that rhythmicity in rate modification techniques may be an important variable for clinicians to consider in their selection of facilitation techniques, because certain rhythmic stimuli may more effectively enhance the learning of altered speaking rates than others. Since the importance of the underlying rhythmic components, inherent in rate modification techniques, is easily overlooked in clinical practice, and since few studies have examined the effects of rate as a function of rhythmicity, the main aim of this study was to explore systematically the differential contributions of rate and rhythm components. For this purpose, we compared sentence intelligibility in hypokinetic dysarthric speakers with PD under 3 different rate conditions (habitual speech rate, and 80% and 60% of habitual speech rate) across two different rhythm pacing conditions (metered vs patterned rhythm).

Materials and methods

Twenty patients with idiopathic PD (16 males, 4 females; mean age 69.5 ± 10.3) participated by voluntary and informed consent in the study. All the patients had been classed as stage III of the Hoehn & Yahr scale (mean disease duration: 8.9 ± 3.2 years). Their speech deficits had to be related to PD and not to other neurological or medical conditions and were assessed, using the Assessment of Intelligibility of Dysarthric Speech (AIDS) (16), upon entry into the study. Additional entry criteria included no on/off fluctuations from current an-

tiparkinsonian medication, adequate hearing, vision and cognition to read out loud, ability to follow an auditory beat with finger tapping and to follow verbal instructions, and no report of cognitive change in the past 6 months interfering with activities of daily living.

Each participant attended two trial sessions during the study. The first session included a motor speech assessment, an assessment of speech intelligibility, reading of 36 experimental sentences within the no-pacing condition (to serve as data baseline), and a training period in which the participant practiced tapping, counting, and reading sentences to a steady auditory metronome beat. The second session included a brief training period of reading sentences synchronized with rhythmic beat patterns. Finally, the two experimental conditions were counterbalanced across participants: metered rhythmic cueing, employing a steady rhythmic pulse on each syllable, and patterned rhythmic cueing, using different beat durations to certain syllables according to the inherent prosodic elements of each sentence. Six blocks of 6 sentences each were read by the participants, each block systematically permuted in its speaking rate (habitual, 80% and 60% of habitual), measured by syllables per minute, and rhythmic presentation (metered vs patterned). Participants first read the target sentence without pacing, then observed the sentence broken into syllables, and then read, one syllable per tone, with and in time to the auditory cue. Auditory cues (tone bursts at 440 Hz) were delivered by the IBM-compatible LOGIC 2.5 program, interfaced through LABTEC loudspeakers at a set volume. Each session was audio-recorded for later analysis on edited cassette tapes, which contained only the intelligibility tests and the experimental conditions. Two outside raters transcribed the speech samples from session 1 and two additional raters rated session 2 (interrater reliability: $r = .91$). Different raters were used for each patient to avoid habituation to and thus improved comprehension of

dysarthric speech due to prolonged exposure. Percentages of accurate word transcriptions were used for statistical analysis via one and two-way ANOVA and paired samples testing.

Results

Mean intelligibility rates improved from 68.9% (pre-test) to 82.5 % (post-test) (Table 1 and Fig. 1). The 19.7% percent increase was

statistically significant (p=.004). Metered and patterned cueing produced similar intelligibility results (metered: 81.2%; patterned: 83.6%). When considering the improvements in intelligibility in relation to the severity of the intelligibility deficit, distinct effects for rhythmic cueing emerged. In the severely affected speakers (n=7; pre-test intelligibility rates below 60%), rates improved from a mean of 44.2% to 85.1 %, an increase of 92.5 percent (p=.001).

Table I - Percentage of speech intelligibility across three baseline levels of impairment

	Total	Below 60%	60-80%	80-90%
PRETEST	68.9±17.9	44.2±8.3	70.1±5.6	84.8±2.0
POST TEST	82.5±12.1	85.1±10.6	77.8±10.9	83.9±13.8
• Metered	81.2±9.7	85.3	79.0	79.6
• Patterned	83.6±14.1	84.9	77.0	88.2

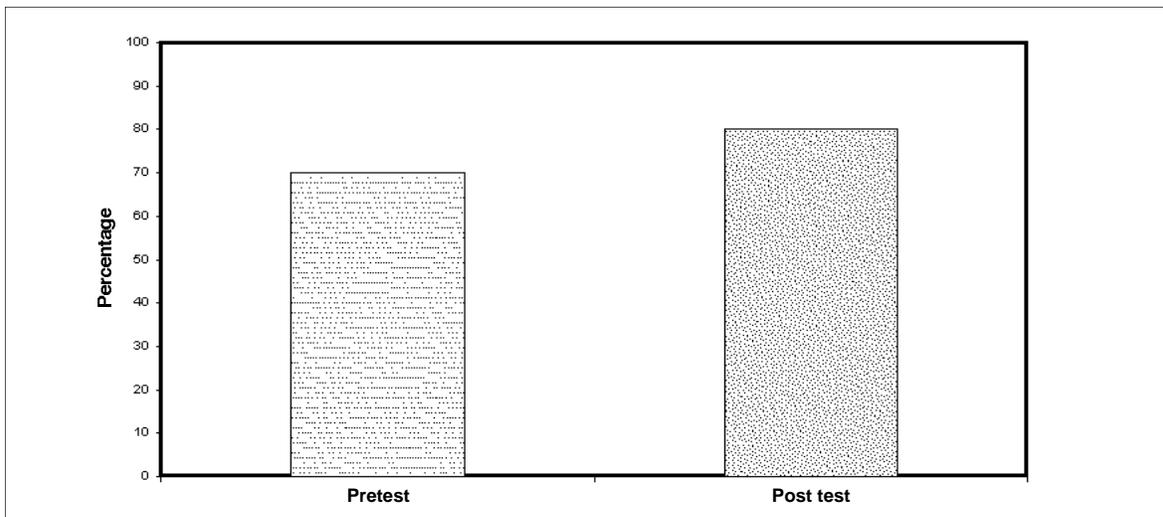


Fig. 1 - Comparison of pretest and post test speech intelligibility.

In the moderately affected group (n=7; intelligibility rates between 60 and 80%), rates improved non significantly from 70.1 to 77.8% intelligibility. In the mildly impaired group (n=6; intelligibility rates between 80 and 90%), intelligibility rates showed no improvement in response to rhythmic speech cueing (pre-test: 84.8%; post-test: 83.9%) (Fig. 2). There were no differences in effectiveness between pat-

terned and metered speech cueing in the severely and the moderately impaired group. In the mildly affected group, metered cueing actually reduced speech intelligibility (79.6%); meanwhile, patterned cueing gave results that were better than those produced by metered cueing but not significantly better than non-cued speech (88.2%) (Fig. 3).

Considering the different rates of speech

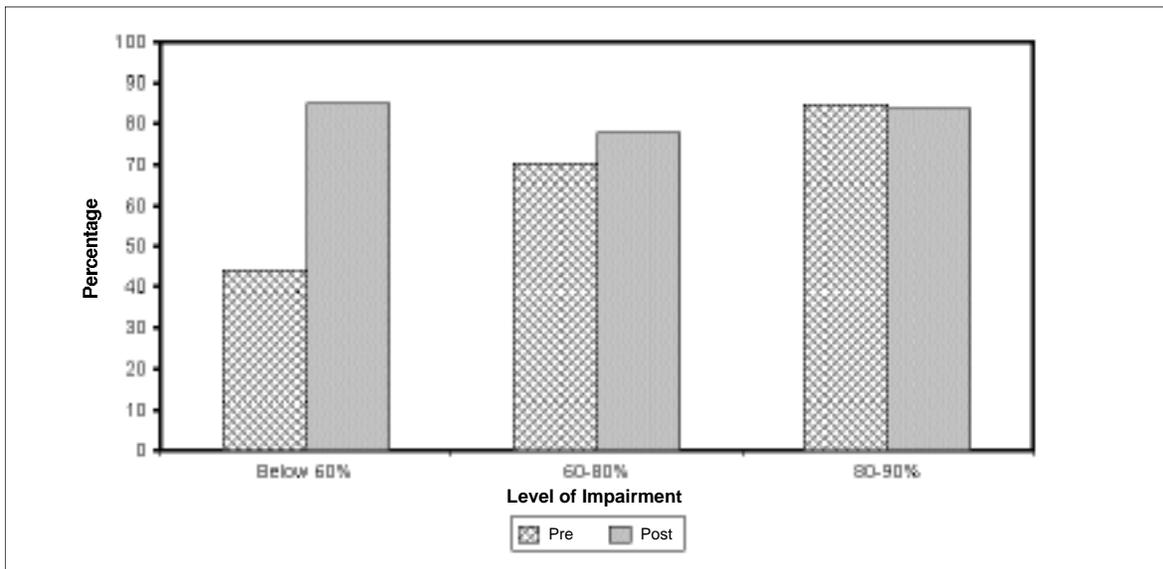


Fig. 2 - Speech intelligibility across three levels of impairment.

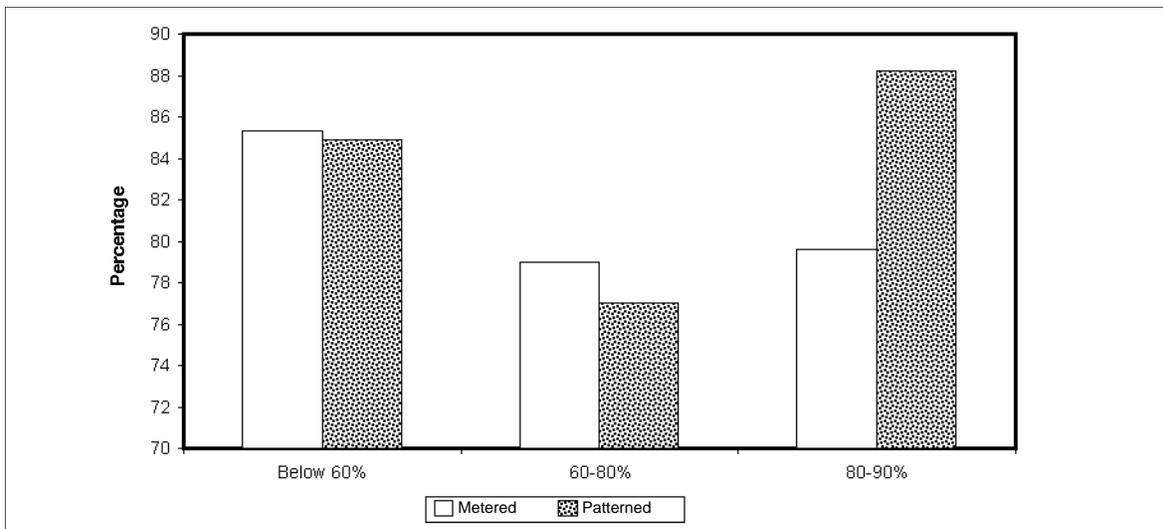


Fig. 3 - Influence of rhythmic speech cueing on intelligibility.

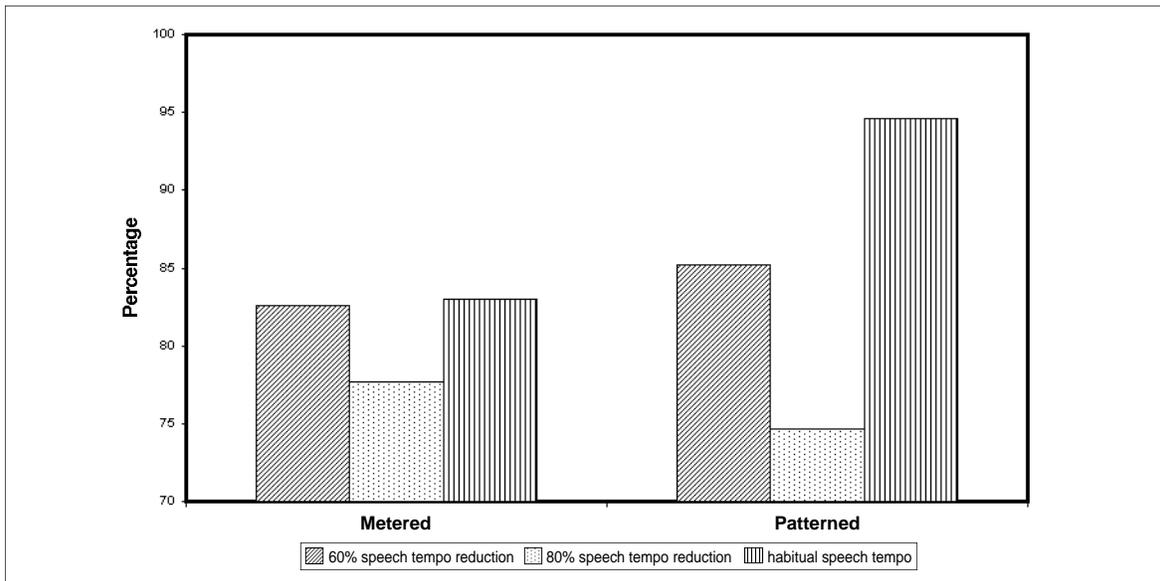


Fig. 4 - Effects of rate and rhythm on speech intelligibility.

cueing, the metered and the patterned rhythm conditions produced similar trends. In both, the rate reduction to 80% produced the weakest intelligibility enhancement (metered: 77.7%; patterned: 74.7%), whereas the habitual and 60 % conditions produced similar intelligibility results (metered habitual: 83.0%; metered 60%: 82.6%; patterned habitual: 85.2%; patterned 60%: 94.6%) (Fig. 4).

DISCUSSION

Rhythmic speech cueing significantly improved speech intelligibility in our study sample of hypokinetic dysarthric speakers with PD. However, when the sample was broken down into subgroups based on severity of speech impairment (mild, moderate, severe), rhythmic speech cueing generated the most substantial enhancement in severely impaired speakers, only slight enhancement in the moderately affected speakers, and no benefit in the mildly impaired speakers. Across subgroups, neither metered nor patterned cueing proved more ad-

vantageous than the other. These results suggest that rigid, temporally constraining techniques such as rhythmic cueing appear to benefit severe intelligibility impairments more than less severe impairments of speech functioning. Similar results have been found in dysarthric speakers with traumatic brain injury (14). Higher levels of speech functioning may benefit more from therapeutic techniques that are less externally constraining. Interestingly, the only real difference in metered vs patterned cueing emerged in the mildly affected speakers who showed improved intelligibility in response to the use of patterned rhythms, which simulated the rhythmic inflections of natural speech, unlike metered cues with their imposition of ‘artificial’ speech rhythm prosody.

When examining the role of rate in speech enhancement, it was noted that in both rhythm conditions the intermediate rate reduction condition (80%) elicited a decrease in speech intelligibility for the total study group. This suggests that in rhythmic cueing optimum speech intelligibility can occur both at one’s natural (habitual) speech rate and at rates that are sub-

stantially different from natural tempi (e.g., 60% in this study). This finding is in line with previous research showing the effectiveness of rhythm and singing to enhance fluency and intelligibility in patients with fluency disorders independent of speech rate (17). When attempting to facilitate speech with external rhythmic cues at frequencies that deviate only slightly from intrinsic frequencies, the proximity of the 2 frequencies may actually produce an interference effect with the attractor function of a natural speech rhythm oscillator and reduce the precision of speech motor output.

In conclusion, the differential benefits of rhythmic cueing depended on rate selection as well as on the patient's level of speech functioning. Rate reduction frequencies close to intrinsic speech rhythms should be avoided due to possible entrainment interference. Rhythmic pacesetting was most successful with severely impaired speakers, showed small improvements in those with moderate impairments, and little or no benefit in mildly affected patients speaking at or above an 80 percent intelligibility rate. Thus, the outcome of our study strongly supports the importance of careful diagnostic assessment to assure differential treatment selection based on scientific evidence and 'best practice' criteria.

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REFERENCES

1. McIntosh GC, Brown SH, Rice RR, Thaut MH. Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. *J Neurol Neurosurg Psychiatry* 1997;62:22-26
2. Thaut MH, McIntosh GC, Rice RR, Miller RA, Rathbun J, Brault JA. Rhythmic auditory stimulation in gait training with Parkinson's disease patients. *Mov Disord* 1996;11:193-200
3. Miller RA, Thaut MH, McIntosh GC, Rice RR. Components of EMG symmetry and variability in parkinsonian and healthy elderly gait. *Electroencephalogr Clin Neurophysiol* 1996;101:1-7
4. McIntosh GC, Rice RR, Hurt CP, Thaut MH. Long-term training effects of rhythmic auditory stimulation on gait in patients with Parkinson's disease. *Mov Disord* 1998;13(Suppl 2):212 (abstract)
5. Rossignol S, Melvill Jones G. Audiospinal influences in man studied by the H-reflex and its possible role in rhythmic movement synchronized to sound. *Electroencephalogr Clin Neurophysiol* 1976;41:83-92
6. Thaut MH, Tian B, Azimi-Sadjadi MR. Rhythmic finger tapping to cosine wave modulated metronome sequences: evidence for subliminal entrainment. *Human Movement Science* 1998b;17:839-863
7. Tecchio F, Salustri C, Thaut MH, Pasqualetti P, Rossini PM. Conscious and unconscious adaptation: A MEG study of cerebral responses to rhythmic auditory stimuli. *Exp Brain Res* 2000; 135:222-230
8. Thaut MH, Miller RA, Schauer ML. Multiple synchronization strategies in rhythmic sensorimotor tasks: period vs phase corrections. *Biol Cybern* 1998a;79:241-250
9. Kenyon GP, Thaut MH. A measure of kinematic limb instability modulation by rhythmic auditory stimulation. *J Biomech* 2000;33:1313-1323
10. Thaut MH, Kenyon GP, Schauer ML, McIntosh GC. The connection between rhythmicity and brain function: implications for the treatment of movement disorders. *IEEE Engin Medic Biol Mag* 1999; 18:101-108

11. Richards CL, Malouin F, Bedard PJ, Cuioni M. Changes induced by L-dopa and sensory cues on the gait of parkinsonian patients. In: Woollacott M, Horak F eds *Posture and Gait: Control Mechanisms*. Eugene OR; University of Oregon Books 1992:126-129
12. Yorkston KM, Beukelman DR. Ataxic dysarthria: treatment sequences based on intelligibility and prosodic considerations. *Journal of Speech and Hearing Disorders* 1981;46:398-404
13. Yorkston KM, Hammen VL, Beukelman DR, Traynor CD. The effect of rate control on the intelligibility and naturalness of dysarthric speech. *Journal of Speech and Hearing Disorders* 1990;55:550-560
14. Pilon MA, McIntosh KW, Thaut MH. Auditory vs visual speech timing cues as external rate control to enhance verbal intelligibility in mixed spastic-ataxic dysarthric speakers: a pilot study. *Brain Inj* 1998; 12:793-803
15. Duffy JR. Managing the dysarthrias. In: Duffy JR ed *Motor Speech Disorders: Substrates, Differential Diagnosis and Management*. St Louis MO; Mosby 1995: 389-416
16. Yorkston KM, Beukelman DR. *Assessment of Intelligibility of Dysarthric Speakers*. Austin; Pro-Ed Publ 1984
17. Glover H, Kalinowski J, Rastatter M, Stuart A. Effect of instruction to sing on stuttering frequency at normal and fast rates. *Percept Mot Skills* 1996;83:511-522

Rhythmic auditory stimulation modulates gait variability in Parkinson's disease. Jeffrey M. Hausdorff, 1,2,3. Patients with Parkinson's disease (PD) walk with a shortened stride length and high stride-to-stride variability, a measure associated with fall risk. Rhythmic auditory stimulation (RAS) improves stride length but the effects on stride-to-stride variability, a marker of fall risk, are unknown. These results demonstrate that RAS enables more automatic movement and reduces stride-to-stride variability in patients with PD. Further, these improvements are not simply a by-product of changes in speed or stride length.