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The efficacy of rhythm-based (mental timing) treatments with subjects with a variety of clinical disorders: A brief review of theoretical, diagnostic, and treatment research

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The efficacy of rhythm-based (mental timing) treatments with subjects with a variety of clinical disorders: A brief review of theoretical, diagnostic, and treatment research

Time and space are the fundamental dimensions of our life and existence (Mauk & Buonomano, 2004). All forms of human behavior require the processing and understanding of sensations received either in *spatial* or *temporal* patterns. Our scientific understanding of the neurobiological mechanisms of *spatial* pattern processing is relatively mature due to 40+ years of research. In contrast, research focused on understanding *mental timing* or *temporal processing* (e.g., time perception, time estimation, interval timing, rhythm perception and production, synchronized motor coordination, etc.) had for many years been the bridesmaid to spatial perception and processing research (Karmarkar1 & Buonomano, 2007). This is no more.

During the past 10 to 15 years (the last five years in particular) major strides have occurred in our scientific and theoretical understanding of human temporal information processing. Our understanding of temporal processing and mental timing, when compared to spatial processing, is still less understood and is at an earlier stage in scientific understanding (Karmarkar1 & Buonomano, 2007; Lewis & Walsh, 2005; Mauk & Buonomano, 2004). This is partially due to a "pleasant problem"—the scientific study of human temporal processing and mental timing is now extensive and spread across a diverse array of disciplines (e.g., neurorehabilitation, biology, neurobiology, neurochemistry, music perception, psychology, neuropsychology, rehabilitation sciences, etc.) and requires "connecting the dots" of research and theory derived from different methods, terminology, and conceptual paradigms. However, even during this formative stage of research and theorization important insights regarding the human mind "timing machine" have emerged. Basic research and theory have led to important developments in understanding typical and atypical human performance across a diverse array of behaviors and competencies. This in turn has led to important applied developments relevant to: (a) the diagnosis of clinical disorders/disabilities (e.g., Parkinson's disease; motor functioning and movement disorders; speech and language disorders; cognitive disabilities; etc.) and, more importantly, (b) temporal or mental-timing based treatment interventions applicable in many education and rehabilitation settings.

Background: Brief summary of key research and theory

It is impossible to summarize in detail (in this brief report) the "state-of-the-art" of human temporal processing or mental timing research and theory. The width and breadth of the literature is tremendous.[3] Below is a list of a primary consensus-based findings[4], findings that lay the foundation for the major focus of this report—a review of the efficacy of rhythm-based treatment interventions for improving human performance in educational and rehabilitation environments.

- The human brain measures time continuously. This capability is important as it subsumes a variety of human performance mechanisms (e.g., temporal processing; rhythm perception and proudction; synchronized motor behavior; etc.) critical to many human behaviors (Lewis, 2005; Nobre & O'Reilly, 2004). It's hard to find any complex behavioral process where mental timing is not involved (Mauk &Buonomano, 2004)
- Timing is essential to human behavior…and we are remarkably proficient at internally perceiving and monitoring time to produce precisely timed behaviors. "We are ready, at any moment, to make complex movements requiring muscle coordination with microsecond accuracy, or to decode temporally complex auditory signals in the form of speech or music" (Lewis & Walsh, 2005, p. 389).
- To deal with time, humans have developed multiple timing systems that are active over more than 10 orders of magnitude with various degrees of precision. These different timing systems can be classified into three general classes (viz., circadian, interval, and millisecond timing), each associated with different behaviors and brain structures/mechanisms (Buhusi & Meck, 2005; Mauk & Buonomano, 2004). The fastest timing system (millisecond or *interval* timing), which is involved in a number of classes of human behavior (e.g., speech and language, music, motor behaviors, attention, cognition, etc.), is the most important timing system for understanding and diagnosing clinical disorders (and atypical development)

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[3] Readers who want more depth and breadth of information should visit a professional blog specifically devoted to human mental time-keeping and temporal processing. The *IQ Brain Clock blog* (http://www.ticktockbraintalk.blogspot.com). Links to the *IQ Brain Clock EWOK (Evolving Web of Knowledge)* provides access to a large collection of original mental timing research and theoretical articles. Links to other relevant blogs, research centers, and mental timing scholars is also available via this web-based resource. A "working" reference bibliography covering the breadth and depth of this literature is included in Appendix C.

[4] Copies of select foundational basic and theoretical research papers are included in Appendix B.

and for developing and evaluating effective treatment interventions for educational and rehabilitation settings. (Buhusi & Meck, 2005; Ivry & Spencer, 2004; Lewis, 2005; Mauk & Buonomano, 2004; Overly & Turner, 2009)

- Although the consensus is that the human brain contains some kind of clock, "determining its neural underpinnings and teasing apart its components have proven difficult" (Lewis & Walsh, 2005, p. 389). This is due to the finding that interval mental timing is not governed by a single anatomical structure or location in the brain but, instead, involves the synchronization of the functions located in a number of brain structures (often in network pathways, circuites or loops), most notably the cerebellum, anterior cingulate, basal ganglia (dopamine), dorsolateral prefrontal cortex, right parietal cortex, motor cortex, and the frontal-striatal loop (Buhusi & Meck, 2005; Casey & Durston, 2006; Lewis & Miall, 2006; Nobre & O'Reilly, 2004; Taub, McGrew & Keith, 2007).
- Research suggests that mental interval timing consists of two sub-systems. The *automatic timing* system processes discrete-event (discontinuous) timing in milliseconds and heavily involves the cerebellum. The *cognitively-controlled timing* system deals with continuous-event timing (in seconds) that requires controlled attention and working memory and primarily involves the basal ganglia and related cortical structures**.** It is the "constellation of several characteristics which determines which timing system is recruited in any particular task" (Lewis & Miall, 2006, p. 401).
- The dominant explanatory model in the research literature is that of a *centralized internal clock* that functions as per the *pacemaker–accumulator model* (PAM; based on scalar timing/expectancy theory; Buhusi & Mech, 2005; Karmarkar & Buonomano, 2007) where "an oscillator beating at a fixed frequency generates tics that are detected by a counter. These models often assume that timing is centralized, that is, the brain uses the same circuitry to determine the duration of an auditory tone and for the duration of a visual flash" (Mauk & Buonomano, 2004, p. 314). However, there is an alternative model where "timing is distributed, meaning that many brain areas are capable of temporal processing and that the area or areas involved depend on the task and modality being used" (Mauk & Buonomano, 2004, p. 314).
  - The predominant "PAM model implicates the processing of temporal information via three synchronized modular information processing systems (see Buhusi & Meck, 2005). The clock system consists of a dopaminergic pacemaker that regularly generates or emits neural ticks or pulses that are transferred (via a gaiting switch) to the accumulator, which accumulates ticks/pulses (neural counting) that correspond to a specific time interval. The raw representation of the stimulus duration in the accumulator is then transferred to working memory, a component of the PAM memory system.

> The contents of working memory are then compared against a reference standard in the long-term (reference) memory, the second component of the PAM memory system. Finally, the decision level of the PAM is conceptualized to consist of a comparator that determines an appropriate response based on a decision rule that involves a comparison between the interval duration value present in working memory and the corresponding duration value in reference memory. In other words, a comparison is made between the contents of reference memory (the standard) and working memory (viz., are they "close?")" (Taub et al., 2007, p. 858-859)

- The extant research suggests that the neural mechanisms underlying mental timing can be *fine-tuned (modified) via experience and environmental manipulation.* More importantly, "interval learning has also been reported to *generalize* across modalities. Nagarajan et al. (1998) reported that training on a somatosensory task can produce improvement on an auditory interval discrimination task similar to the interval used for somatosensory training. Even more surprising, training on an auditory task appears to result in an interval-specific improvement in a motor task requiring that the subjects tap their fingers to mark specific intervals (Meegan et al. 2000)" (Mauk & Buonomano, 2004, p. 317-318). *Modifiability* of mental interval timing and subsequent *generalization* suggest a *domain-general timing mechanism* that, if harnessed via appropriately designed timing-based interventions, may be able to produce both specific and generalized changes in a variety of human behaviors.

Temporal processing/mental timing and clinical disorders: Brief research bibliography and comments

An important component of any theory or model of human functioning is the application of the theory to typical and atypical development. The bulleted summary above primarily reflects basic research focused on normal or typical human temporal processing and mental time-keeping. For a theory to have applied relevance, particularly in educational and rehabilitation settings, research must demonstrate that individuals with diagnosed clinical disorders (or atypical development) develop these core temporal processing abilities differently and/or have an impairment or deficit in their "mental timer" that produces observable behavioral symptoms and disruption of functional performance.

During the past 15 years, to those who have cast a wide net for mental timing research across multiple disciplines, an explosion of research in this area is obvious. This extant literature has clearly identified atypical or disordered temporal processing as a core component (or a partial component and/or symptom) of a variety of clinical disorders and/or atypical functioning. Space does not allow a comprehensive review of this literature (which would likely fill multiple chapters in a book). For the purposes of the current manuscript we have listed a select (not exhaustive) set of research studies (categorized by diagnostic disorder or domain of human functioning) that collectively support the importance of various dimensions of temporal processing (e.g., time perception, time estimation, interval timing, synchronized coordinated movements, rhythm perception and production, time production, temporal order judgment, auditory temporal sequencing, temporal resolution, etc; see titles of references below) in understanding a variety of diagnostic disorders. The conclusion is obvious—*temporal processing or mental time-keeping is important in understanding (and potentially diagnosing) a wide variety of human conditions*, such as ADHD, age-related deficits and declines (e.g., Alzheimers), motor coordination and production disorders (e.g., apraxia, CP, gait), Parkinson's disease, schizophrenia, speech and language disorders (e.g., dysfluency, aphasia, apraxia), traumatic brain injury (TBI), and possibly a variety of other conditions (e.g., autism). Not included in the list below is an extensive collection of studies linking temporal processing characteristics and problems in reading skill acquisition (e.g., dyslexia—see Appendix C).

Skeptics may question how such a diversity of disorders across such a vast range of human performance domains can all be impacted by a similar core brain-based mechanism (i.e., the "brain clock"). It is our interpretation of the literature, as touched on in the brief theory review above, that the basic human temporal processing mechanism (mental timing; the brain block; or whatever term a researcher may use) is a domain-general mechanism. Briefly, domain-general (versus domain-specific) brain or cognitive mechanisms are not tied to any specific content or domain and influence a wide range of novel problems and domains of human performance. They are often referred to as "*Jack-of-all-trades*" mechanisms (Chiappe & McDonald, 2005). An example from cognitive psychology is the notion of general intelligence (*g*), which contemporary research suggests involves the domain-general mechanisms of executive functioning, working memory, and controlled executive attention. Of particular interest is recent research (Buhusi & Meck, 2005; Helmbold, Troche & Rammsayer; Helmbold, Troche & Rammsayer, 2006; Rammsayer & Brandler, 2002; Rammsayer & Brandler, 2007) that suggests that *g* (general intelligence) may have at its core *neural efficiency* guided by a *master internal mental clock* (temporal *g*). See Taub et al. (2007) for a detailed explanation of the hypothesis that an internal mental clock-driven temporal processing mechanism, based on the synchronization and coordination of neural functions in different parts of the brain (e.g., dorsolateral pre-frontal cortex; cerebellum; basal ganglia; frontal-striatal loop or circuit), may account for the central and common role of temporal processing and mental timing across such diverse conditions and domains of human functioning.

ADHD and related behaviors

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Ben-Pazi, H., Shalev, R. S., Gross-Tsur, V., & Bergman, H. (2006). Age and medication effects on rhythmic responses in ADHD: Possible oscillatory mechanisms? Neuropsychologia, 44(3), 412-416.

Gilden, D. L., & Marusich, L. R. (2009). Contraction of time in Attention-Deficit Hyperactivity Disorder. Neuropsychology, 23(2), 265-269.

Glicksohn, J., Leshem, R., & Aharoni, R. (2006). Impulsivity and time estimation: Casting a net to catch a fish. Personality and Individual Differences, 40(2), 261-271.

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Aging-related disorders (dementia, Alzheimers, etc.)

Baudouin, A., Vanneste, S., Isingrini, M., & Pouthas, V. (2006). Differential involvement of internal clock and working memory in the production and reproduction of duration: A study on older adults. Acta Psychologica, 121(3), 285-296.

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Motor coordination, timing, and rhythm disorders (e.g., gait, stroke, cerebral palsy, swallowing, etc.)

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Parkinsons’s disease

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Schizophrenia

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Speech and language disorders (dysfluency, aphasia, apraxia, etc.)

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Efficacy of rhythm-based intervention/treatment studies: Brief research summary

When attempting to bridge basic research/theory and practice, in this case in educational or rehabilitation settings, a three-legged stool is desirable—*theory → diagnosis/classification →treatment/intervention*. In the previous sections (and the appendices) we presented support for research and theory-based model(s) of human temporal processing or mental time-keeping (*leg one*). *Leg two* was presented next in the form of a sizeable research literature base indicating that the measurement of temporal processing may identify a core domain-general brain-based mental-timing mechanism that may facilitate the diagnosis and classification of a variety of clinical disorders or conditions of atypical development. Does evidence exist for *leg three*—effective brain timing-based interventions and rehabilitation programs?

Identification of interventions/treatments. To answer this question, we reviewed the most prominent treatment interventions that, either implicitly or explicitly, use as their treatment core one or more central characteristics of mental-time keeping or temporal processing. A review of the literature revealed four primary treatments based on a central feature of human temporal processing—*rhythm perception and production*. To save space we present, in Table 1, the rational, description, operational definitions, and comparisons of the similar rhythm-based characteristics of the four treatment techniques: *Rhythmic Auditory Stimulation* (RAS), *Rate and/or Rhythm Treatments for Apraxia of Speech* (AOS)—(AOS-RRT), *Melodic Intonation Therapy* (MIT), and *Synchronized Metronome Tapping* (e.g., *Interactive Metronome*®--IM).

A review of the final column in Table 1 "cuts to the chase" regarding the similarities of the RAS, AOS-RRT, MIT, and IM treatments. All invoke the use of *timing and rhythm techniques* to train subjects to *synchronize* a targeted behavior (e.g., speech fluency, speech intelligibility, language, motor coordination of upper and lower extremities) to an *externally provided target rhythm* (i.e., entrainment). We consider all four treatments as using a similar form of *auditory pacing/entrainment*. A *common feature* is the employment of *external beat or rhythm tools* (tapping to a beat, metronome-based rhythmic pacing, rhythmic cuing via timed pulses/beats) to guide a subjects performance. Although we believe these similar central timing mechanisms and tools argue for reviewing the efficacy of treatment outcome studies across all four treatment approaches, it is important to recognize that the treatments do vary on a number of other characteristics—use of music or melodic patterns (RAS, MIT), the targeted behaviors (e.g., speech vs limb coordination), and the incorporation of real-time performance (IM).

Identification of rhythm-based intervention studies. A review of the research literature found 23 treatment studies that employed a rhythm-based intervention consistent with the treatment definitions presented in Table 2. We believe these 23 studies should be considered illustrative (and not exhaustive). We did not conduct a detailed systematic literature search that is typically associated with journal-based narrative or meta-analytic research syntheses (Cooper, 1998). We are confident that other published and unpublished treatment studies exist. The purpose of this review was not to be an all-encompassing "talking stalk" of the extant literature. Instead, this review should be viewed as an exploratory attempt to ascertain whether additional efforts should be expended in conducting more research, attempting larger and more systematic research syntheses, and whether clinicians and educational and rehabilitation agencies should be encouraged to continue and/or explore the use of rhytm-based treatments with a variety of clients. As such, our review used three primary methods to identify potential studies: (a) a limited and select keyword search of the PsycINFO and IAP Reference databases[5] for studies published during the past 10 years, (b) a similar keyword search of the internet via Google, (c) a review of research studies available via the previously cited mental timing blog[3], and (c) an ancestral reference search of studies identified via the first three methods. The 23 studies are organized and summarized in Table 2.

<u>Summary of research on rhythm-based mental-timing treatments</u>. Given the stated goal of the current review (see above), and the heterogeneity of study characteristics, we inspected the results of Table 2 with one goal…to answer the question: "*does sufficient evidence exist to support the temporal processing (mental time-keeping) <u>theory→diagnosis/classification→treatment</u> three-legged stool ?*" With a few caveats, we believe that collectively the preponderance of positive outcomes (across the 23 listed studies) indicates that *rhythm-based mental-timing treatments have merit for clinical use and warrant increased clinical use and research attention*.

As summarized in Table 2, positive treatment outcomes were reported for all four forms of rhythm-based treatment. Positive outcomes were also observed for normal subjects and, more importantly, across a variety of clinical disorders (e.g., aphasia, apraxia, coordination/movement disorders, TBI, CP, Parkinson's disease, stroke/CVA, Down's syndrome, ADHD). Given the wide range of subject types, sample sizes (some small case studies to small-medium sized group studies, with and without control groups), variable statistical rigor, and differing target behaviors, it is not possible to disentangle the results to identify treatment interactions and specific effects by diagnostic category or condition. One notable observation of interest is that *<u>15 of the 23 studies (the RAS, AOS-RRT and SMT treatment studies) all employed some form of auditory-based metronome</u>* to pace or cue the subjects targeted rhtymic behavior. In all other studies, rhythm-pacing used some form of manual tapping or beat sound (e.g., drum). We conclude that *the use of external metronome-based rhythm tools (tapping to a beat,*

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[5] IAP Reference database described at: http://tinyurl.com/dcvrdm

metronome-based rhythmic pacing, rhythmic-cuing via timed pulses/beats) is a central tool to improving temporal processing and mental-timing.

On balance, we conclude that the preponderance of reported positive treatment effects reported in Table 2, be they for group or small clinical case studies, suggests that *rhythm-based treatment programs typically produce positive treatment outcomes*. *It is our position that the positive outomces for rhythm-based treatment programs argue for additional clinical use and research*. To extend and improve on the posistive treatment outcomes for rhythm-based treatment programs, we recommend :(a) more extensive and systematic reviews of the treatment literature, (b) replication of many of the studies with larger samples where subjects are randomly assigned to treatment and control groups, (c) additional studies that investigate long-term post-treatment effects, and (d) studies that compare the relative efficacy of the different rhythm-based treatment programs (RAS, AOS-RRT, MIT, SMT). In addition, we urge those interested in rhythm-based treatment development and research make greater efforts to incorporate the extensive knowledge that has emerged from basic and theoretical temporal processing and mental time-keeping research—with an eye toward improving current treatments and/or developing even more effective treatments.

Concluding comments

It is beyond the scope of this brief report to hypothesize about all possible explanations of the positive treatment outcomes produced by a class of similar (yet different) rhythm-based treatments. As discussed previously in this paper, given the converging research that points toward a possible neurologically-based domain-general internal mental-timing mechanism (i.e., a potentially modifiable internal brain clock), it is possible that the efficacy of all four classes of rhythm-based treatments are operating (in their own way) on "*fine tuning the temporal resolution of the human brain clock.*" Our *temporal resolution fine-tuning hypothesis* is consistent with the *temporal resolution power (TRP) hypothesis* (Rammsayer & Brandler, 2002, 2007) that indicates that oscillatory brain process are responsible for the efficiency and speed of neural-based information processing. We hypothesize, via the temporal resolution fine-tuning hypothesis, that the positive outcomes for rhythm perception and production-based treatments may be due to these treatments increasing the efficiency and speed of information processing in brain-based neural networks responsible for the planning, execution and synchronization of complex human behaviors.

We urge both academic and applied researchers to embrace the temporal processing (mental timing) *theory→diagnostic/classification→treatment* literature reviewed in this report and increase efforts to understand the links between the three legs of the mental timing stool. The positive effects of current "*brain rhythm*" treatment programs for many types of disorders, across a variety of human performance domains, is encouraging, particularly when placed in the context of the emerging science and theory of the human brain clock.

Table 1: Description, definition and comparison of primary rhythm-based (mental time keeping; temporal processing) treatment interventions.

Treatment	**Operation definition and description of treatment**	**Similarities between treatments**
Rhythmic Auditory Stimulation (RAS)	Rhythmic Auditory Stimulation (RAS) was developed primarily by Thaut, McIntosh, & Rice at The Center for Biomedical Research in Music at Colorado State University. RAS is a Neurologic Music Therapy technique that utilizes the physiological effects of rhythm on the motor system to increase the efficiency of controlled movement patterns during rehabilitation. Clinical research on rhythmic auditory stimulation (RAS) demonstrates the effectiveness of rhythmic time cuing, demonstrating significant improvements in walking function of those with Parkinson's disease and in survivors of stroke. The enhancement of motor skills (i.e., rehabilitation of hemiplegic arm or gait) is mediated by an entrainment effect where movement frequencies and motor programs entrain to rhythm through anticipatory cuing of functional movement patterns. During RAS, there is an immediate entrainment stimulus providing rhythmic cues during movement, such as listening to music with strong rhythmic pulse while walking to enhance walking tempo, balance, and control of muscles and limbs. Patients train with RAS for a prescribed period of time in order to achieve more functional gait patterns which they then transfer to walking without rhythmic facilitation. Mechanisms of RAS for gait training include: rhythmic entrainment, priming of the auditory pathway, cuing of the movement period, and step-wise limit cycle entrainment. The physiological basis for the perception of rhythm is the detection of periodicity patterns in amplitude modulations of sound. An external rhythm serves as an external oscillator which has a "magnet" effect on one's internal timekeeper. The strength of the effect is substantiated by the observation that motor responses can be entrained by rhythmic patterns even at levels that are imperceptible. The physiological entrainment of muscle activation through rhythm perception takes place via reticulospinal pathways. Neurons in the spinal cord become excited as a result of auditory perception. Research has shown that many components of the neural synchronization network were already activated and "entrained" simply by listening to rhythm. One result of neuronal excitement is the "priming" or "readying" of muscle groups utilized in movement, which has a facilitative effect on subsequent motor functioning. Kinematic models show that period (or frequency) entrainment results in enhanced kinematic stability through the stabilization of the following parameters: acceleration, velocity, and trajectory. Recent application of RAS therapy to the stroke-affected arm and hand has shown similar effects of rhythmic cuing on rehabilitating functional movements. In this paradigm, the participant is cued by a stable metronome-like auditory stimulus to reach from one target to another, which produces movement mimicking functional reach. Studies using RAS therapy demonstrate a significant reduction in the variability of timing and reaching trajectories in stroke survivors. Compared to self-paced movements, RAS reduces the instances of accelerations and decelerations during reaching movements, resulting in smoother movements. RAS therapy has three advantages for retraining arm movement post-stroke: 1. The rhythm ensures that the same movement is efficiently produced over repetitive trials. 2. The rhythmic cuing provides an attentional goal during reaching movements. Goal setting is also known to enhance movement control and to promote re-learning of movement skills. 3. The rhythmic facilitation cued by an auditory stimulus, provides the participant with sensory feedback regarding the movement requirements. Feedback is another factor which encourages movement learning. The motivational quality of music is a bonus secondary effect (i.e., client preferences can be used). However, some diagnoses do not perceive complex acoustic patterns well so very simple music or simply a metronomic click works best.	• Invokes use of timing & rhythm to improve motor planning & sequencing motor skills of upper and lower extremities • Form of auditory pacing/entrainment

Rate and/or Rhythm Treatments for Apraxia of Speech (AOS)—(AOS-RRT)	An underlying premise of the treatments that have focused on rhythm and/or rate is that Apraxia of Speech (AOS) is characterized by disruptions in the timing of speech production (Dworkin & Abkarian, 1996; Tjaden, 2000; Wambaugh & Martinez, 2000). Furthermore, rhythm is considered to be an essential component of the speech production process. It has been suggested that rhythm control treatments for AOS may help to re-establish temporal patterning (or metrical processing, Brendel et al., 2000). More specifically, it has been hypothesized that central pattern generators (CPGs) are involved in speech production (Barlow, Finan, & Park, 2004) and may be dysfunctional in AOS (Dworkin & Abkarian, 1996). Rhythmic treatments, such as metronomic pacing, are a form of entrainment (phase-locking of movements/rhythms), which may help to reset or improve function of CPGs (Wambaugh & Martinez, 2000). Although speakers with AOS typically exhibit reduced rate, further slowing of speech production is thought to provide additional time for motor planning and/or programming as well as for processing of sensory feedback. Several suggestions regarding attentional motivations for employing rate/rhythm controls have been made. Dworkin et al. (1988) suggested that their metronomic treatment may have served to focus the patient's attention on the need for additional precision in speech production. Conversely, Brendel et al. (2000) hypothesized that their rhythmic control treatment may have provided an external focus of attention in that attention may have been directed towards matching the external stimulus and was consequently drawn away from the actual speech movements. Targets for treatment with rate/rhythm strategies are systematically manipulated in terms of perceived increased complexity to meet individual patient needs. For example, Dworkin et al. (1988) began treatment with a bite-block activity in which the speaker raised and lowered her tongue tip to the beat of the metronome. Treatment progressed to alternate motion rate (AMR) practice, then to multisyllabic word practice, and finally to sentence production. Other treatment targets have included reiterative nonsense syllables (e.g., dadada; Tjaden, 2000), isolated vowels and vowel combinations (Dworkin & Abkarian, 1996), and oral reading (Southwood, 1987). Rate/rhythm control treatments for AOS may provide benefits for some individuals with AOS. Gains may be seen in the form of improvement of articulation, increased fluency, reduced rate, or decrease in overall AOS symptoms. *From Journal of Medical Speech Pathology (June 1, 2006)*	• Invokes use of timing & rhythm to improve motor planning & sequencing for intelligible speech • Form of auditory pacing/entrainment
Melodic Intonation Therapy (MIT)	Melodic intonation therapy (MIT) was developed by neurological researchers Sparks, Helm, and Albert in 1973 for the rehabilitation of nonfluent aphasia. Because music and language structures are similar, it is suspected that by stimulating the right side of the brain, the left side will begin to make connections as well. Researchers noted that "increased use of the right hemisphere for the melodic aspect of speech increases the role of that hemisphere in inter-hemispheric control of language, possibly diminishing the language dominance of the damaged left hemisphere" (Marshal and Holtzapple 1976:115). For this reason, patients are encouraged to sing words rather than speak them in conversational tones in the early phases of MIT. Studies using positron emission tomography (PET) scans have shown Broca's area (a region in the left frontal brain controlling speech and language comprehension) to be reactivated through repetition of sung words. The effectiveness of MIT derives from its use of the musical components timing, melody and rhythm in the production of speech. To accomplish this, a practitioner employing MIT takes common words and phrases and turns them into melodic phrases emulating typical speech intonation and rhythmic patterns (Davis et al. 1999, Marshal and Holtzapple 1976, and Carroll 1996). The traditional MIT process is divided into four progressive stages. However, modifications are often made to meet the specific needs of the patient. This is one reason why it is difficult to obtain definitive research results in MIT. In the early stages, MIT was used solely for adult patients, but eventually therapists began to use MIT with children. Therapists found that the traditional procedure did not work well with children, so a new three level structure was developed by Helfrich-Miller (Roper 2003).	• Invokes use of timing, rhythm, & melody to improve speech & language • Form of auditory pacing/entrainment

Synchronized Metronome Tapping (SMT)	Taub et al. (2007) define a class of interventions as *synchronized metronome training* (SMT). These treatments, in general, require a subject to maintain synchrony (via a bimanual motor response) with auditory tones (e.g., from a metronome). Tapping in synchrony with a metronome requires an individual to correct for asynchronies in their response to a reoccurring beat. The Interactive Metronome® (IM) is the most prominent SMT treatment program. IM is a structured, goal-oriented timing and rhythm intervention that is based upon similar principals to that of Rhythmic Auditory Stimulation (RAS). Rather than use of music, patients are instead instructed to synchronize hand and foot movements to a computer-generated reference tone (metronome) heard through headphones. As the patient attempts to match the rhythmic beat with repetitive motor actions such as tapping his/her toes on a floor sensor mat or hand clapping while wearing an IM glove with palm trigger, a patented guidance system provides immediate real-time auditory and/or visual feedback for timing and rhythm. The difference between the patient's performance and the computer-generated beat is measured in milliseconds and an average millisecond score is provided at the conclusion of each exercise. A lower millisecond score (closer to the reference beat) indicates better accuracy and timing. IM settings are programmable so that the pacing of exercises is appropriate for the motor/processing needs of each individual patient. IM is typically not provided as a stand-alone treatment, but is integrated into a more comprehensive treatment program. There exists an abundance of neuroscientific research on the critical role of temporal processing (or the brain's internal timing mechanisms) for many human performance domains, including praxis, motor coordination, gait, information processing, and speech/language. The sensorimotor feedback provided by IM during each exercise enables the patient to systematically improve timing & rhythm essential for optimal recovery of function following acquired neurological insult or onset of neurological disease.	• Invokes use of timing & rhythm to improve motor planning & sequencing motor skills of upper and lower extremities, speech, processing, and language • Unlike other forms of auditory entrainment/RAS, IM provides critical real-time feedback to promote improved temporal processing (critical for recovery of aforementioned performance domains) • Form of auditory pacing/entrainment

Table 2. Summary of select rhythm-based intervention studies across various clinical and non-clinical subjects.

Source[6]	**Treatment** [7]	**Sample Description**	**Outcome (dependent) variables**	**Method and data analysis**	**Summary of Results**
Hausdorff et al. (2007)	**RAS:** RAS beat step rate set at 100 to 110% of each subject's usual cadence (via a metronome). RAS effects evaluated under six different conditions.	N = 29 patients (Mean age = 67.2 yrs) with Parkinson's Disease (PD); N = 26 (Mean age = 64.6 yrs) healthy age-matched controls.	Gait performance: Stride time variability (a marker of fall risk), swing time variability, and spatial-temporal measures. A computerized force-sensitive system was used to quantify gait rhythm, timing of the gait cycle (i.e. the stride time), swing time and stride-to stride.	Mixed effect models for repeated measures comparison of within-group and between-group mean score differences.	For the PD subjects, RAS at 100% significantly improved gait speed, stride length and swing time (p < 0.02) but did not significantly affect variability. With RAS at 110%, significant reductions in variability were also observed for PD subjects (p < 0.03). Positive effects persisted 2 and 15 min post-treatment. Positive effects of RAS were not observed in control subjects.
Kenyon & Thaut (2000)	**RAS:** RAS presented free-field as a metronome click, which was frequency-matched to the step frequency recorded and computed for the trial without RAS. One full gait cycle was recorded.	N = 5 (Mean age = 32 years) traumatically brain-injured (TBI) patients with gait hemiparesis.	Lower extremity knee tremor. Residual absolute value sums (RAVS) analysis of tremor-like perturbations of knee angle during the gait cycle.	Subject performance compared (via dependent sample *t*-tests) to mathematical-model developed normal (control) simulated subject tremor data.	For the RAS treatment subjects, the RAVS-measured gait cycle knee tremor was significantly reduced by 39.5%
Kwack (2007)	**RAS:** Three week intervention. Both a metronome and drum were used during training and practice to confirm the accuracy of the tempo and to assist in synchronizing the subject's gait.	N = 25 subjects (6 to 20 years old) with spastic cerebral palsy (CP).	Gait performance: Cadence, stride length, velocity, and symmetry ratio data collected via the Stride Analyzer.	Pre/post-test *t*-test design with two treatment groups (therapist-guided training-TGT, N=9; self-guided training-SGT, N=7) compared to control (N=9) group.	According to the author, the results supported three conclusions: "(a) RAS does influence gait performance of people with CP; (b) individual characteristics, such as cognitive functioning, support of parents, and physical ability play an important role in designing a training application, the effectiveness of RAS, and expected benefits from the training; and (c) velocity and stride length can be improved by enhancing balance, trajectory, and kinematic stability without increasing cadence." The two treatment groups showed 5% (STG) and 1.2% (TGT) improvement in cadence, but this was not significantly different from control. Overall strength level improvement was 15.8% (STG/TGT combined) with the TGT group showing a significant improvement over the control of 29.5 %. Overall velocity improvement was 20.7 5 (STG/TGT combined) with the TGF group increase of 36.5% significantly higher than control group.

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[6] Complete reference citations are included in the Reference Section of this document. Copies of each article are included in Appendix A.

[7] Brief descriptions/definitions of treatments are included in Table 1. RAS = Rhythmic Auditory Stimulation; AOS-RRT = Apraxia of Speech: Rate or Rhythm Treatment ; MIT = Melodic Intonation Therapy; SMT = Synchronized Metronome Training;

Thaut et al. (1996)	**RAS:** Three weeks of daily training that consisted of audiotapes with metronome-pulse patterns embedded into the on/off beat structure of rhythmically accentuated instrumental music.	N = 37 subjects with Parkinson's Disease (PD). N = 15 in treatment group. Two control groups (N =11 per group). Mean age ranged from 69-74 years across groups.	Gait performance: Cadence, stride length, and velocity. Additionally, EMG recordings of the medial gastrocnemius (GA), tibialis anterior (TA), and vastus lateralis (VL) muscles on both sides (averaged across five stride cycles) was obtained.	ANOVA of pre/post-test change scores. RAS treatment group (N= 15) performance, for each outcome measure, compared to performance of internally self-paced treatment control group (N = 11) and control group (N = 11) receiving no treatment.	Subjects receiving RAS treatment significantly (p < 0.05) improved their gait velocity by 25%, stride length by 12%, and step cadence by 10% *more* than self-paced subjects (one control group) who improved their velocity by 7% and no-training subjects (second control group) whose velocity decreased by 7%. In the RAS-group, timing of EMG patterns changed significantly (p < 0.05) in the anterior tibialis and vastus lateralis muscles. "Evidence for rhythmic entrainment of gait patterns was shown by the ability of the RAS group to reproduce the speed of the last training tape within a 2% margin of error without RAS."
Thaut et al. (1997)	**RAS:** Six weeks of twice/day training that consisted of audiotapes with metronome-pulse patterns embedded into the on/off beat structure of rhythmically accentuated instrumental music.	N = 20 subjects with hemiparetic strokes randomly assigned to RAS treatment and control groups. Mean age was 72-73 years for groups.	Gait performance: Cadence, stride length, velocity, and swing symmetry. Additionally, EMG recordings of the medial gastrocnemius (GA) muscles was obtained across five stride cycles.	Percentage change scores were computed for each subject and averaged across groups. Percent change scores were used to offset pre-test group differences. Nonparamtetric Mann-Whitney rank-order tests were used for statistical analysis of group differences.	Pre/post-test measures revealed a statistically significant (p< 0.05) increase in velocity (164% vs 107%), stride length (88% vs 34%), and reduction in EMG amplitude variability of the gastrocnemius muscle (69% vs 33%) for the RAS-training group compared to the control group. The difference in stride symmetry improvement (32% in the RAS-group vs 16% in the control group) was not statistically significant.
Thaut et al. (2002)	A **rhythmic model of rehabilitative motor training (rate control pacing)** based on rhythmic cueing on spatiotemporal control of sequential reaching movements Patients asked to move their paretic arm in time to a rhythm (touching sensors on the beat) with and without (counter-balanced) metronome-based cueing.	N = 21 right-handed patients (mean age = 52.7 years) with confirmed left hemispheric CVAs (cerebrovascular accident)	Reaching performance: Arm timing, wrist trajectories, elbow and shoulder kinematics, wrist velocity/acceleration/position profiles and rhythmic synchronization.	Time series analysis. ANOVA, dependent sample *t*-tests and nonparametric dependent sample test's (Wilcoxon Signed Rank).	Statistically significant (P <0.05) improvement in patiotemporal arm control during rhythmic entrainment and reduction of variability of timing and reaching trajectories Time series analysis found immediate reduction in variability of arm kinematics during rhythmic entrainment within the first two to three repetitions of each trial. Rhythm also produced significant increases in angle ranges of elbow motion (P < 0.05). Significant kinematic smoothing was found during rhythmic cuing. Rhythmically cued acceleration profiles fit the predicted model data significantly closer (P <0.01) than the self-paced profiles.

Thaut et al. (2007)	**RAS:** Three weeks of daily training. Compared RAS to NDT/Bobath treatment. Established RAS training protocols using a metronome and specifically temporally prepared music	N = 78 subjects with hemiparetic strokes randomly assigned to RAS treatment and control groups. Mean age was 69.2 and 69.7 years for two different treatment groups.	Gait performance: Cadence, stride length, velocity, and swing symmetry.	Pre/post-test *t*-test design with two treatment groups. RAS group (n = 43) performance compared to performance of group (n = 35) receiving NDT/Bobath treatment.	Pre/post-test measures showed a significant improvement in the RAS group for velocity (*p* = .006), stride length (*p* = .0001), cadence (*p* = .0001) and symmetry (*p*= .0049) over the NDT/Bobath group. Effect sizes for RAS over NDT/Bobath training were 13.1 m/min for velocity, 0.18 m for stride length, and 19 steps/min for cadence. Gains were significantly higher for RAS compared to NDT/Bobath training.
Mauszycki & Wambaugh (2008)	**AOS-RRT:** Subject was trained to produce multisyllabic words and phrases in rhythm using a combination of digital metronome (audible click plus small flashing light) and hand tapping. Treatment was twice a week sessions (30–45 minutes) until the subject reached at least 90% accuracy in tapping and syllable production to the beat of the metronome in two consecutive treatment sessions or until 10 treatment sessions were completed.	N = 1 case study of 35 year old subject with chronic mild acquired apraxia of speech (AOS)and aphasia	Speech production: Production of multisyllabic words, phrases and sentences.	A single-subject multiple baseline design across outcome variables. Analysis of percent change (and trend lines) across treatment sessions. Conservative dual-criterion method (CDC) used for analysis of trends. Magnitude of the trend line difference from baseline to treatment estimated using the D-index calculation of Effect Size (ES).	According to the authors, the “treatment resulted in an improvement in sound production accuracy in an individual with AOS and aphasia. Positive changes were observed for treated four syllable words, phrases, and untrained four-syllable words, although treatment did not directly target sound production accuracy (i.e., feedback was not given regarding accuracy of productions).’’ The magnitude of the difference in baseline probe data compared to treatment phase probe data for 4 syl.-2nd words yielded an ES-index of 5.57 (large effect). ES-index of 2.39 (small effect size) suggested a reliable treatment effect for 4 syl.-3rd words. For untreated 4 syl.-2nd words the ES index was 1.79 and for untreated 4 syl.-3rd words the ES-index was 1.32 (small effects)—“suggesting that treatment resulted in some positive changes in sound production accuracy (generalisation) for untrained four-syllable words.”
Pilon et al. (1998)	**AOS-RRT:** Three different rhythm synchronization rate control procedures (auditory metronome cuing, singing, and board pacing) were investigated (in counterbalanced order) and subject performance was compared across methods and a baseline no pacing condition Each subject participated in one session per week for a total of 6 weeks.	N = 3 three male (23-44 years of age) post traumatic brain injury (TBI) patients with mixed spastic-ataxic dysarthria.	Speech rate and intelligibility: Speech rate measured as words per minute (wpm). Speech samples were obtained when reading functional sentences. Verbal intelligibility was measured by the percentage of total words in a transcribed speech sample.	Single-subject research design with baseline reversal (ABACAD). Data were analyzed visually by plotting wpm and intelligibility data in two-D graphs. Statistical analysis employed Analysis of Variance procedures (ANOVA) with planned comparisons to study the difference between treatment conditions and a Pearson Product Moment Correlation analysis to study the relationship between wpm and intelligibility scores.	Statistically significant (p < 0.05) changes in increased speech intelligibility during all three pacing conditions for the two more involved subjects. Differences between treatment conditions were not statistically significant. However, auditory metronome cuing showed the best results for the two subjects who benefited from rate control. The authors concluded that “the performance of speakers in this investigation suggested that external pacing for the purpose of reducing speaking rate and increasing speech intelligibility may be beneficial when there is at least moderately severe impairment; but may be detrimental to overall speech intelligibility when there is only mild speech impairment. For the speakers in this investigation for whom speech rate modification was beneficial, findings suggested that auditory rhythmic cueing was preferable to visuospatial cues, not only for increasing speech intelligibility but also for effectively modulating speech to a target rate.”

Belin et al. (1996)	**MIT:** Subjects heard and repeated words under conditions with or without MIT intonation and rhythmic tapping. MIT not used as long-term therapy but as one condition under which to observe active brain functioning (CBF; PET).	Seven right-handed severe nonfluent aphasic patients with left MCA infarct. Aged 40 to 58 years (Mean = 49.7 years)	Changes in relative cerebral blood flow (CBF). Brain areas measured included Broca's area (and right hemisphere homologue), prefrontal area, temporal pole, anterior superior temporal gyrus, middle temporal gyrus, Heschl's gyri, Wernicke's area (and right hemisphere homologue), parietal area, and mouth sensorimotor area.	CBF assessed under four different conditions: Rest--subjects were asked to remain at rest. Hearing--subjects listened to a list of words read with a natural intonation by one of the investigators. Simple Repetition--subjects heard and then repeated each word of a new list, read with a natural intonation by the same investigator. Repetition with MIT--the investigator read the words of a new list with an MIT-like intonation, and the subjects were instructed to repeat each word with the same intonation. Wilcoxon's rank sum test used to evaluate statistically significance of changes.	Authors reported that "without MIT, language tasks abnormally activated right hemisphere regions, homotopic to those activated in the normal subject, and deactivated left hemisphere language zones. In contrast, repeating words with MIT reactivated Broca's area and the left prefrontal cortex, while deactivating the counterpart of Wernicke's area in the right hemisphere" The MIT condition resulted in relative CBF decreases in seven out of nine right hemisphere regions of interest. Statistically significant CBF changes reported the right homologue of Wernicke's area (p < 0.02). In the left hemisphere, there was a statistically significant relative CBF increase in Broca's area, and in the adjacent prefrontal cortex (p < 0.04).
Bonakdarpour et al. (2003)	**MIT:** Intoned (sung phrases) patterns to exaggerate the normal melodic content of speech at three levels of difficulty. Included the rhythmic tapping of each syllable while phrases are intoned and repeated. 15 1.5 hour sessions per week.	N = 7 clinical case study Persian subjects with severe nonfluent aphasia (age range 45-61; Mean age = 52 years). 5 subjects classified as having Broca's aphasia and two with subcortical aphasia.	Speech production performance: Select portions of the Farsi Aphasia Test (FAT). Measures of confrontational and responsive naming, word discrimination, commands, and NCCU (number of correct content units–adapted from Index of Lexical Efficacy).	Analysis of Pre/post-test outcome variables with Wilcoxon signed-rank (non-parametric) test.	Statistically significant improvement in phrase length (P = 0.125), number of correct content units (P = .0107), confrontational naming (P = .0312), responsive naming (P = .0107), repetition (P = .0084), word discrimination (P = .0238), and commands (P = .0238). Non-targeted variables (e.g., reading an writing test scores) showed no significant improvement, as expected.

Carroll (1996)	**MIT:** Intoned (sung phrases) patterns to exaggerate the normal melodic content of the target phrases. Included the rhythmic beat (drum) of each syllable while phrases are intoned and repeated. Children received the same treatment during 12-weekly 30-minute individual sessions,	N = 8 young children (3 to 6 years of age) with Down syndrome, matched on the basis of mean length of utterance (MLU) randomly assigned to one of two groups--spoken or melodic (MIT). All subjects received the same treatment during 12-weekly 30-minute individual sessions, except for the manner in which target phrases were presented: Spoken versus melodically intoned (MIT). A drum was used with all the children to support the rhythmic patterns of the target phrases.	Speech production: Total number of words, mean length of utterance, and rate of response (time required to produce 100 consecutive utterances). Verbal responses during each weekly session were categorized according to the nature of the response: unison, imitative, conversational and spontaneous	Multivariate repeated measures analysis of variance (MANOVA) was calculated on each of the measures to determine whether the pre/posttest gains between groups differed significantly. Pearson product-moment correlations measured the degree of association between pre- and posttest scores.	A comparison of the pre-and post-intervention scores for the total number of words and rate of response revealed similar differences between the melodic and spoken groups. There was a marginal effect for total number of words for both groups (p = .057), with the effect attributed to greater intervention gains for the MIT group. Statistically significant group differences for rate of response (P <.05) with children in the MIT producing utterances in a significantly shorter period of time (required half as much time than they did in the pre-intervention language sample: r = .994; P < .01). Children in the MIT group also experimented more with the target phrases by modifying, extending or transforming them. A marginally significant effect was found for the mean length of utterance (MLU; P =.060) due to the gains in the MIT group.
Schlaug et al. (2008)	**MIT:** Intoned (sung phrases) patterns to exaggerate the normal melodic content of speech at three levels of difficulty. Included the rhythmic tapping of each syllable while phrases are intoned and repeated. Five 1.5 hour sessions per week until patient meets specified treatment criteria. Total of 75 sessions.	N = 2 clinical case study subjects with severe nonfluent aphasia as the result of a left hemisphere ischemic stroke involving mainly the superior division of the middle cerebral artery. Classified as having Broca's aphasia. Patient #1 received MIT treatment while Patient # 2 (received alternative SRT therapy that did not include two key MIT features; melodic intonation and rhythmic tapping). After SRT Patient #2 then received same MIT treatment.	Speech production performance: Average number of Correct Information Units (CIUs)/min and the average number of syllables/phrase during speaking and singing. Subjects were also given confrontational picture naming tasks, including the Boston Naming Test and a matched subset (30 images) of the Snodgrass-Vanderwart color pictures.	No formal statistical analysis due to case study design. Clinical inspection of changes in outcome measures.	Between-treatments comparison (Patient #1 MIT vs. Patient #2 SRT) made after 40 sessions showed that the MIT-treated patient had greater improvement on all outcomes than the SRT treated patient. fMRI studies revealed that Patient #1 showed significant fMRI changes in a right-hemisphere network involving the premotor, inferior frontal, and temporal lobes, while Patient #2 had changes in a left hemisphere network consisting of the inferior pre- and post-central gyrus and the superior temporal gyrus. Following the post 40-SRT assessment, Patient #2 was enrolled in the MIT treatment, and the post 40 scores became the new baseline from which the effects of MIT was measured. After 40 MIT sessions Patient #2 showed a further increase in speech output and picture naming, and his post 75-MIT assessments revealed further gains in speech output while the picture-naming score remained stable.

Wilson et al. (2006)	**MIT:** Thirty novel phrases were generated and allocated to one of three experimental conditions: unrehearsed, rehearsed verbal production (repetition), and rehearsed verbal production with melody (MIT). The unrehearsed condition served as the control for the rehearsed conditions (i.e., the effect of no intervention). The rehearsed conditions entailed twice-weekly practice sessions for a period of 4 week. Rehearsed verbal production assessed the effects of practice using an accentuated rhythm as opposed to melody during training.	N = 1 case study. A right-handed, 53 year old amateur male musician with severe Broca's aphasia. Subject had sustained a left middle cerebral artery tertiary stroke.	Speech production. Proportion of words correctly produced, Phrase length (covariate), and qualitative analysis of types of speech production errors as a function of phrase group.	*t*-test and repeated measures analysis of covariance (ANCOVA) of subjects speech performance across conditions.	Statistically significant better performance for phrases rehearsed using MIT versus those rehearsed using repetition (P < .05). Performance of the MIT and repetition phrases was statistically significantly better than performance of the unrehearsed phrases across time (baseline and follow-up 1). In contrast, the difference between the subject's overall performance of the MIT and repetition phrases was not significant. The authors concluded that during MIT therapy the subject "was significantly more likely to reach the stage where he could answer a question with a sung target phrase than a spoken phrase. Although sung or spoken rehearsal had a short-term beneficial effect on his word production compared with no training, the effects of MIT were more durable, facilitating superior phrase production 5 weeks after therapy. MIT phrases were also more commonly produced without a prompt and were more likely to be complete utterances."
Belin et al. (1996)	**MIT:** Subjects heard and repeated words under conditions with or without MIT intonation and rhythmic tapping. MIT not used as long-term therapy but as one condition under which to observe active brain functioning (CBF; PET).	N = 7 right-handed severe nonfluent aphasic patients with left MCA infarct. Aged 40 to 58 years (Mean = 49.7 years)	Changes in relative cerebral blood flow (CBF). Brain areas measured included Broca's area (and right hemisphere homologue), prefrontal area, temporal pole, anterior superior temporal gyrus, middle temporal gyrus, Heschl's gyri, Wernicke's area (and right hemisphere homologue), parietal area, and mouth sensorimotor area.	CBF assessed under four different conditions: Hearing--subjects listened to a list of words read with a natural intonation by one of the investigators. Simple Repetition--subjects heard and then repeated each word of a new list, read with a natural intonation by the same investigator. Repetition with MIT--the investigator read the words of a new list with an MIT-like intonation, and the subjects were instructed to repeat each word with the same intonation. Wilcoxon's rank sum test used to evaluate statistically significance of changes.	Authors reported that "without MIT, language tasks abnormally activated right hemisphere regions, homotopic to those activated in the normal subject, and deactivated left hemisphere language zones. In contrast, repeating words with MIT reactivated Broca's area and the left prefrontal cortex, while deactivating the counterpart of Wernicke's area in the right hemisphere" The MIT condition resulted in relative CBF decreases in seven out of nine right hemisphere regions of interest. Statistically significant CBF changes reported the right homologue of Wernicke's area (p < 0.02). In the left hemisphere, there was a statistically significant relative CBF increase in Broca's area, and in the adjacent prefrontal cortex (p < 0.04)

Bartscherer & Dole (2005)	**SMT:** Interactive Metronome (IM) intervention for improving timing and rhythm via synchronized metronome-based training. 15 sessions over 7 weeks.	N = 1 case study of 9 year old with motor coordination (Impaired Neuromotor Development) and attention problems.	Fine and gross motor performance and observed behavior: Pre/Post-testing on Bruininiks-Oseretsky Test of Motor Proficiency (BOTMP). Anecdotal parent report of changes in behavior at home. IM session timing accuracy performance indicators.	No formal statistical analysis due to N = 1 case study design. Clinical inspection of changes in BOTMP gross and fine motor scores and changes in IM "off of beat" across time (graph of all sessions performance).	The authors reported that "the child improved in the gross motor composite from performance in the 3rd percentile to the 6th percentile. In the fine motor composite, he improved from the 1st percentile to the 14th percentile." The authors suggested these were clinically significant changes. Clinical analysis of raw score changes suggested "largest improvements in balance, response speed, visual-motor control,and upper limb speed and dexterity." Anecdotal parent reports suggested some changes "related to motor function but most of which were related to affective or organizational behavior."
Gleason and Trujillo (2008)	**SMT:** Interactive Metronome (IM). 8 treatment sessions performed while either standing or sitting (dependent on functional skill level of subjects). IM treatment compared to group that received standard home care program range of motion (ROM) exercise routines.	N = 6 subjects with confirmed CVA (cerebrovascular accident). Three subjects each in the IM treatment and ROM groups. Mean age was 61 and 60 years respectively.	Upper extremity and finger dexterity performance. Change in upper extremity fluidity/speed (as per the IM measurement system) and finger dexterity and timing (Nine Hole Peg test). Jebsen Hand Function Test. (measure of rhythm and timing, motor planning and sequencing, and attention; upper and lower extremity unilateral and bilateral movements).	Pre/post-test design with no formal statistical difference tests. Percentage change in outcome variables.	Improvement in upper extremity performance (as measured by IM rhythm synchronization scores) in both IM and ROM groups. Authors concluded that these pilot study results supported IM as a compliment to standard ROM treatment.
Grieshop and Trujillo (2009)	**SMT:** Interactive Metronome (IM). 8 treatment sessions performed while either standing or sitting (dependent on functional skill level of subjects. Subjects subsequently checked for long-term change 45 days later (with no intervening treatment). .	N = 2 subjects with confirmed CVA (cerebrovascular accident).	Upper extremity and finger dexterity performance. Change in upper extremity fluidity/speed (as per the IM measurement system) and finger dexterity and timing (Nine Hole Peg test) . Jebsen Hand Function Test. (measure of rhythm and timing, motor planning and sequencing, and attention; upper and lower extremity unilateral and bilateral movements). Canadian Occupational Performance Measure (COPM), a measure of subject's self-perception and satisfaction with occupational performance.	Pre/post-test design with no formal statistical tests. Percentage change in outcome variables.	COPM Post assessment revealed a perceived improvement and satisfaction in performance and satisfaction with writing a check and lowered satisfaction with opening a jar. All other COPM scores remained unchanged Both subjects made notable motor gains as per performance on the IM measurement system. Both subjects also improved their Nine-hole Peg test timed scores. Inspection of the Jebsen Hand Function test also indicated some improvement. Both subjects commented on functional improvements such as being able to now fold a towel, to get dressed more easily, to have more natural movements, and to have less tone. The authors suggested that these reported "improvements suggest an increase in efficiency of motor planning and sequencing and thus better motor output." 45-day post-treatment revealed that the motor gains were maintained and subsequently improved upon. The COPM suggested small changes in participant's perceptions of their performance and satisfaction.

Libkuman (2002)	**SMT:** Interactive Metronome (IM) intervention for improving timing and rhythm via synchronized metronome-based training. 12 sessions over a period of 5 weeks.	N = 40 volunteer golfers (normal non-clinical disorders) randomly assigned to two groups. IM treatment group or control group (read how to improve golf swing). Mean age was 31 to 37 years across groups.	Golf swing performance. Golf shot distances from target as measured by the Full Swing Golf Simulator.	ANOVA for repeated measures (Pre/post-test scores).	The participants in the SMT (IM) experimental group demonstrated statistically significantly (P < .05) improved accuracy relative to the participants in the control condition, who did not show any improvement.
Schaefer et al. (2001)	**SMT:** Interactive Metronome (IM) intervention for improving timing and rhythm via synchronized metronome-based training. 15 sessions.	N = 56 boys (6 to 12 years of age) with ADHD. Subjects randomly assigned to IM treatment group or one of two control groups (no treatment; video games).	Attention/concentration, motor functioning, language, behavior, reading & writing achievement. Tests of Variables of Attention (TOVA); Conners' Rating Scales–Revised; Achenbach Child Behavior Checklist; The Sensory Profile; select motor tests (to measure bilateral coordination and upper-limb coordination, speed, from Bruininks-Oseretsky Test for Motor Proficiency (BOTMP); Wide Range Achievement Test (WRAT 3) reading & writing tests; Language Processing Test.	Analysis of Variance procedures (ANOVA) for repeated measures (Pre/post-test scores).	A statistically significant (p < .0001)pattern of improvement across 53 of 58 variables favoring the Interactive Metronome treatment group was reported. Significant differences were found among the treatment groups and between pretreatment and post treatment factors on performance in areas of attention, motor control, language processing, reading, and parental reports of improvements in regulation of aggressive behavior.
Taub et al. (2007)	**SMT:** Interactive Metronome (IM) intervention for improving timing and rhythm via synchronized metronome-based training. 18 50-minute sessions over a 3-4 week period.	N = 86 students (7 to 10 years of age) attending a public elementary charter school receiving Title 1. Subjects randomly assigned to IM treatment or control (recess activities). IM treatment provided in small group setting with each subject having individual IM apparatus.	Reading achievement, cognitive-related reading abilities, timing and rhythmicity. Woodcock-Johnson (WJ III) reading achievement tests, Tests of Oral Reading Fluency (TOWRE), Test of Silent Word Reading Fluency (TSWRF), and Comprehensive Test of Phonological Processing (CTOPP).	Multivariate analysis of covariance (MANCOVA). Pre/post-test scores).	The IM treatment group, when compared to the control group, demonstrated statistically significant (P < .001) improvements (close to a two standard deviation increase) in measured timing and rhythmicity scores (as measured by the IM measurement system), reading efficiency and fluency (P = .009), statistically significantly higher phonological processing scores, but no statistically significant change in reading level (non-speeded) scores (P > .05). When converted to Hedge's *g* effect size statistic, the statistically significant findings translated to increased proficiency for the IM group (over the control group) of 15-20%. The authors concluded that the increased efficiency of timing and rhythmicity produced significant improvements in the basic or fundamental reading skills (e.g., letter-naming speed; phonological processing) and reading efficiency/fluency…but not overall increases in reading level abilities (i.e., unspeeded single word sight word recognition).

Trujillo et al (2006)	**SMT:** Interactive Metronome (IM) 8 treatment sessions performed while seated in stable chair. Pilot study to evaluate short vs. long IM treatment protocol.	N = 6 subjects (23 to 86 years of age). Healthy young to older normal adults with no identifiable disability.	Upper extremity performance. Change in upper extremity fluidity and speed, as per the IM measurement system.	Pre/post-test design with no formal statistical tests. Percentage change in outcome variables. A prior pilot study established expected endurance levels for different adult age groups (based on number of repetitions over 5 minute period).	This was a pilot IM-specific study that demonstrated that notable changes in IM-measured rhythm synchronization scores were achievable with a shortened IM treatment protocol. The subjects in the 20-30 year age range demonstrated 57% mean change in upper extremity fluidity and speed. Subjects in the 40–60 year old group demonstrated 45 % improvement. 61% mean score improvement was reported for the subjects in the 60–90 year group.
Trujillo et al (2007)	**SMT:** Interactive Metronome (IM) 8 treatment sessions performed while seated in stable chair.	N = 12 subjects (55 to 68 years of age). Healthy older normal adults with no identifiable disabling diagnosis	Upper extremity and finger dexterity performance. Change in upper extremity fluidity/speed (as per the IM measurement system) and finger dexterity and timing (Nine Hole Peg test)..	Pre/post-test. Percentage change in outcome variables.	Statistically significant improvement in upper extremity performance (as measured by IM rhythm synchronization scores; P =.039). Statistically significant change in Nine Hole Peg test finger dexterity scores (P = .009).

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