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IMPROVEMENTS IN INTERVAL TIME TRACKING AND EFFECTS ON READING ACHIEVEMENT

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This study examined the effect of improvements in timing/rhythmicity on students' reading achievement. 86 participants completed pre- and post-test measures of reading achievement (i.e., Woodcock-Johnson III, Comprehensive Test of Phonological Processing, Test of Word Reading Efficiency, and Test of Silent Word Reading Fluency). Students in the experimental group completed a 4-week intervention designed to improve their timing/rhythmicity by reducing the latency in their response to a synchronized metronome beat, referred to as a synchronized metronome tapping (SMT) intervention. The results from this *non-academic* intervention indicate the experimental group's post-test scores on select measures of reading were significantly higher than the non-treatment control group's scores at the end of 4 weeks. This paper provides a brief overview of domain-general cognitive abilities believed effected by SMT interventions and provides a preliminary hypothesis to explain how this *non-academic* intervention can demonstrate a statistically significant effect on students' reading achievement scores. © 2007 Wiley Periodicals, Inc.

In recent years the role of the school psychologist has expanded to include greater involvement in students' reading acquisition, performance, and curriculum-based evaluation. This increased participation may be attributed to several national initiatives including Reading First under No Child Left Behind (U.S. Department of Education, 2002), the National Reading Panel's (2000) report, the Individuals with Disabilities Education Improvement Act (2004), and the impact of empirical research in reading on district- and state-level policies and procedures (e.g., Daly & McCurdy, 2002; Sheridan, 2004). Recent technological advancements also provided school psychologists with a broader understanding of the process of reading at a physiological level. Results from neuroscience studies (e.g., functional magnetic resonance imaging investigations involving individuals experiencing reading difficulties or diagnosed with dyslexia) have provided new insights into the process of reading at the neural level (e.g., see Katzir & Paré-Blagoev, 2006). This groundbreaking research has demonstrated individual differences in the functions of anatomically similar brain regions of impaired readers and nonimpaired readers (Katzir & Paré-Blagoev, 2006; Shaywitz & Shaywitz, 2005; Shaywitz et al., 1999, 2003).

The integration of our understanding of the process of reading at a physiological level with reading at a behavioral level (i.e., neuroscience-based interventions) may be the next frontier for school psychologists and reading research. One intervention that has received considerable empirical attention, both pro and con, is the FastForWard method (Tallal, Miller, Jenkins, & Merzenich, 1997). A lesser known neuroscience-based intervention is the use of synchronized metronome tapping, which links research on mental interval timekeeping (e.g., see Buhusi & Meck, 2005) and academic achievement. Preliminary results from this research indicate that children diagnosed

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with dyslexia may have deficiencies in their timing and rhythm abilities, as evidenced by their responding within a wider range of times on either side of a metronome beat, when compared to nonimpaired readers (Wolff, 2002). Similarly, McGee, Brodeur, Symons, Andrade, and Fahie (2004) reported children diagnosed with a reading disability differed from children diagnosed with attention-deficit/hyperactivity disorder (ADHD) on retrospective time perception, a finding interpreted as consistent with Barkley's (1997) behavioral inhibition theories. Research also implicated mental or interval timekeeping (time perception) in a number of academic and behavioral disorders (see McGee et al., 2004). Some researchers believe the connection between timing/rhythm and reading may be so robust that a student's mean latency response to a metronome beat may predict performance on standardized reading tests (Waber et al., 2003; Wolff, 2002). Furthermore, a recent study has suggested that elementary timing tasks may represent a form of *temporal g* that is more strongly correlated ($r = .56$) with psychometric *g* than the standard *reaction time g* ($r = -.34$) approach to measuring the *essence* of general intelligence (Rammsayer & Brandler, in press). Given the growing evidence suggesting a potentially important link between mental interval timekeeping and cognition and learning (Buhusi & Meck, 2005; Rammsayer & Brandler, in press), the connection between timing-based neuroscience interventions (e.g., synchronoized metronome tapping) and academic achievement warrants investigation.

To investigate the relationship between improvements in timing and rhythm (due to synchronized metronome tapping-based intervention) on reading achievement, Taub, McGrew, & Lazarus (2007) administered subtests from the Woodcock-Johnson Tests of Achievement III (WJ-III ACH; Woodcock, Mather, & McGrew, 2001) as pre- and posttest measures of reading. In this study, over 250 high-school-aged participants were randomly assigned to either a control or experimental group. The experimental group participated in a rhythmic synchronization metronome-based assessment and intervention technique (herein after referred to as the Interactive Metronome [IM] method), a *nonacademic* intervention. The IM treatment sessions lasted for approximately 45 minutes each day for total of about 15 hours. (The IM intervention method will be discussed in detail below.) The results from this study indicated, when compared to the control group, the experimental group demonstrated statistically significant improvements on the WJ-III ACH posttest measures of broad reading and reading fluency. Participants who received IM-based interventions also demonstrated statistically significant improvements in domains other than reading.

IM training was also reported to produce positive effects in a number of nonacademic domains. For example, after receiving IM training, participants demonstrated statistically significant improvements in golf performance (Libkuman & Otani, 2002). Shaffer et al. (2001) reported that boys prediagnosed with ADHD demonstrated improved performance, when compared to two ADHD control groups, in the domains of attention, language processing, motor control, reading, and parent report of regulation of aggressive behavior after their participation in an IM-based intervention.

Mental Interval Timing Research and Models

Cognitive psychology's interest in mental timekeeping has spanned decades. For example, cognitive differential psychologists first reported the identification of a *temporal tracking* capability in 1980 (Stankov, Horn, & Roy, 1980). Temporal tracking was identified as being found in various auditorily presented tasks that involved the mental counting or rearrangement of temporal sequential events (e.g., reorder a set of musical tones; Carroll, 1993).

Researchers in cognitive psychology have studied the phenomenon of *interval timing* through a number of research paradigms, one which requires individuals to maintain synchrony (via a bimanual motor response) with auditory tones (e.g., from a metronome), also known as synchronized metronome tapping (SMT). Tapping in synchrony with a metronome requires an individual to correct for asynchronies in their response to a reoccurring beat. The most viable theoretical explanation for SMT behavior can be derived from the pacemaker-accumulator model, which is based on scalar timing/expectancy theory (see Buhusi & Meck, 2005). Briefly, SMT asynchrony corrections are thought to be accomplished through an internal adjustment to the phase of one's underlying master mental time clock (Buhusi & Meck, 2005; Vorberg & Fuchs, 2004). This error correction is triggered when observed temporal deviations (as determined via the accumulation, in a short-term storage *accumulator*, of neural pulses or tics from a cognitive *pacemaker*) are determined to differ from a reference *standard* (which is maintained in a *reference memory*), via performance feedback. This process is referred to as an *automatic phase adjustment*. The allocation of *attentional resources* and the minimization of stimuli that may divert cognitive processing resources away from timing have been hypothesized to play a significant role in mental interval timekeeping and metronome-based synchronization of rhythmic movements (Brown & Bennett, 2006; Buhusi & Meck, 2005). In addition, the quickness and efficiency of the phase adjustment mechanism is believed to eliminate the necessity for, or excessive reliance on, long-term memory (e.g., accessing the reference memory) or learning (Vorberg & Fuchs, 2004).

How SMT-Based IM Training Works

During IM training participants wear a headphone and listen to a reoccurring metronome beat. As they listen to the beat, they engage in physical movements such as clapping hand-to-hand with a sensor on one palm as they match their physical movement to the presentation of the beat (e.g., clap at the beat). The goal of IM training is to reduce the mean negative synchronization error during normal tracking of the regularly occurring metronome beat (clapping prior to or past the beat).

During training, participants receive feedback through an auditory guidance system as they progress through the simple, interactive physical movements. Although feedback is also provided through visual stimuli, the auditory feedback guidance system is the primary feedback method. The auditory feedback system provides tonal stimuli that indicate whether the participant responded *prior to*, *at*, *or past* the regularly occurring auditory metronome beat. The accuracy of participants' expectancy response to the metronome beat is provided in milliseconds (ms), with different tones indicating *far from*, *close to*, or *at* the metronome beat. A visual reading of millisecond latency is also presented on a computer screen.[1] The purpose of IM training is to improve participants' timing/rhythmicity by reducing the latency between the onset of the metronome beat and participant's expectancy response to the beat. After about 3–4 weeks of training, or 15–18 hours, participants are typically able to respond to within approximately 15 ms on either side of the beat. This compares to the average 80–100 ms latency response prior to training. At the completion of training, participants typically have engaged in approximately 25,000 motoric repetitions. These movements are the physical indication of one's expectancy of the onset of the metronome beat. Collectively, results from initial studies suggest that statistically significant improvements in a *domain-specific* SMT-based intervention are associated with statistically significant *domain general* improvements in the areas of academics, ADHD, and sports. How can rhythmic SMT-based interventions result in improved performance across such diverse domains of human performance as academics, ADHD, golf, and tennis?

[1]Readers are referred to the Interactive Metronome, Inc.'s Web site to view a corporate-sponsored video showing IM training or to obtain additional information: http://www.interactivemetronome.com.

Purpose

Although hypothesized domain-specific cognitive mechanisms are possible, the domain-general or cross-domain SMT training effect is intriguing and argues first for replication of prior studies and second for investigation of potential domain *general* cognitive mechanisms to account for observed cross-domain improvements. Given this assumption, the purpose of this study was twofold.

The first purpose was to replicate an earlier study by examining the impact of improvements in timing/rhythmicity on students' reading achievement. The second purpose was to offer preliminary hypotheses that will contribute to a better understanding of the across-domain general cognitive mechanisms that may explain SMT treatment effects across such diverse human performance domains as academics, ADHD, and sports.

Method

Participants

Study participants included 86 students attending a public charter school receiving Title 1 funding located in Central Florida. As a public charter school, the school is a part of the public school system; the key difference between the public charter school and a public school is that the charter school receives funding directly from the State of Florida. The school currently has 133 students and provides education from kindergarten through fifth grade. All students attending the school are African-American, and 83% of the students receive free lunch. The study participants ranged in grade from first to fourth grade. There were 16 first-, 36 second-, 23 third-, and 11 fourth-grade students in the study. A total of 37 participants were male and 48 were female. Participants' ages ranged from 7 years old to 10 years old with a mean of 8.15 years ($SD = 1.0$).

Instruments

The instruments administered to evaluate the effects of IM training on participants' academic achievement and attention/concentration include selected subtests of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999), Test of Silent Word Reading Fluency (TOSWRF; Mather, Hammill, Allen, & Roberts, 2004), Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999), and the WJ-III ACH (Woodcock et al., 2001). Table 1 provides a brief description of each test and identifies the specific subtests administered from each instrument.

Reliability

Most of the reported average internal consistency and alternate form reliability coefficients of the CTOPP exceed .80 and the test–retest coefficients range from .70 to .92 (Wagner, Torgesen, & Rashotte, 1999). The reported average alternate forms' reliability coefficients of the TOWRE all exceed .90 and the test–retest coefficients range from .83 to .96 (Torgesen, Wagner, & Rashotte, 1999). The median reliability coefficients of the tests selected from the WJ-III ACH are all at or above .87 (McGrew & Woodcock, 2001).

A lesser know test was the Test of Silent Word Reading Fluency. This instrument was standardized on 3592 individuals representing demographic characteristics that were similar to the 2001 U.S. Census data in terms of geographic region, gender, race, ethnicity, and parents' educational background. The instrument's normative tables are grouped in 3-month intervals for students ages 6-6 through 7-11, 6-month intervals for students 8-0 through 10-11, and at 1-year intervals for students ranging from 11-0 through 17-11 years of age. Reported test–retest reliabilities

Table 1
Names and Description of the Pretest and Posttests

Test	Description of tests and combinations of tests
Test of Oral Word Reading Efficiency	*Sight Word Efficiency*: A timed test of word recognition and decoding fluency, measures the ability to accurately and quickly recognize familiar words *Phonemic Decoding Efficiency*: A timed test measuring the ability to accurately and quickly read phonetically regular nonsense words. *Total Word Reading Efficiency*: Combines Sight Word Efficiency and Phonemic Decoding Efficiency.
Test of Silent Word Reading Fluency	Students are presented with several rows of words, which increase in difficulty. There are no spaces between the words (e.g., didhimgot). Students are required to draw a line between the boundaries of as many words as possible (e.g., did/him/got) within a 3-min time limit.
The Comprehensive Test of Phonological Processing	*Blending Nonwords*: Phonetic coding synthesis task of nonwords—an auditory processing task that is independent of acquired knowledge (less dependent on students' existing knowledge). *Segmenting Nonwords*: Phonetic coding analysis task of nonwords—an auditory processing task that is independent of acquired knowledge. *Rapid Digit Naming*: Rapid automatized naming test of digits. *Rapid Letter Naming*: Rapid automatized naming test of letters. *Rapid Naming Composite*: Combines Rapid Digit Naming and Rapid Letter Naming. *Alternate Phonological Awareness Composite*: Combines Blending Nonwords and Segmenting Nonwords.
Woodcock-Johnson III Tests of Achievement	*Letter-Word Identification*: Untimed measure of sight-word recognition. *Passage Comprehension*: Measure of reading comprehension and word knowledge. *Reading Fluency*: A timed test measuring reading speed, automaticity and rate of test taking. *Word Attack*: Untimed test requiring pronouncing nonwords that conform to English spelling rules.

for students ranging in age from 7 to 10 years of age, the age range of the present study, were all above .80, and the alternate form reliability coefficients exceeded .85 (Mather et al., 2004).

Procedure

All students completed a pretest battery of psychoeducational instruments (see Table 1). After completing the pretests, students were randomly assigned to either an experimental or control group. The experimental group participated in the IM intervention, at their school, during regular school hours. While the experimental group was participating in the IM intervention, the control group and nonparticipating classmates engaged in recess activities. Students in the experimental group were divided into four groups, one for each grade level. Two certified master trainers worked separately with each of the four grade-level groups. The groups ranged in size from 7 to 12 participants. The students in the experimental group participated in an average of 18 sessions, each lasting approximately 50 minutes. There was one treatment session each day per group. Upon completion of the IM intervention, posttests were administered to all participants. The same tests were used during the pre- and posttest administrations.

Participants completed both individually and group administered tests; however, the TSWRF and WJ-III ACH's Reading Fluency were the only group-administered tests. During the individual assessment each evaluator worked with a student one on one. The individual assessment took approximately 35 minutes to complete. Group administrations were conducted in the students' own classrooms and participants from the experimental and control group completed all group tests together as classmates. Students who were unable to participate and/or who were absent on the day of the group assessments completed the group tests either individually or with other nonclassmate students. During all test administrations the test proctors and administrators were unaware of each student's group assignment. A lead test administrator directed all group assessments. The administrator followed the standardized instructions included in each test's manual. For one test, WJ-III ACH Reading Fluency, minor modifications were made in standardized administration procedures to facilitate group administration of the test. Several steps were followed to ensure that standardized test administration procedures were followed as closely as possible. These steps included (a) a doctoral-level proctor was present during all group administrations, (b) a minimum of one proctor to every four students was maintained during all group administrations, (c) all test proctors were graduate-level school psychology students who either completed or were near completion of their second psychoeducational assessment course, and (d) if a student did not accurately complete a sample item, the group administration was stopped and the proctor followed standardized administration procedures to ensure adequate completion of the sample item. All students progressed through the group test administration at the same time.

Results

Unless otherwise noted, all analyses controlled for pretest scores using the same measure as the posttest (through analysis of covariance). For analyses that did not use developmentally based scores, such as raw or growth scores, age was also controlled in the analyses by entering age as a covariate in the ANCOVA. Given the prediction that statistically significant differences would favor the experimental group, one-tailed tests ($\alpha = .05$) were used to evaluate statistical significance.

Effects on Timing/Rhythm

The initial analysis examined the effect of IM training on timing and rhythm as measured by the IM assessment system. The IM treatment had a statistically significant effect on posttest timing and rhythm scores, with pretest score controlled, $F(1,76) = 107.376$, $p < .001$. Furthermore, the treatment had a large effect (Thompson, 1999) on the posttest outcome ($\eta^2 = .586$, $g = 1.974$). IM training accounted for more than 50% of the variance in IM posttest scores and resulted in close to a two standard deviation increase in those scores (with IM pretest scores controlled).

It seems likely that IM training should be more effective for children who initially showed poor performance (high scores) on the measure of timing and rhythm. Sequential multiple regression was used to evaluate the possibility of a statistically significant interaction between the pretest and treatment. The IM posttest was regressed on the centered IM pretest and group membership in one block, with the centered pretest by group cross-product entered in a second block. As summarized in Table 2, the addition of the cross-product to the regression resulted in a statistically significant increase in R^2, indicating that the Pretest $\times$ Treatment Group interaction was statistically significant. The nature of the interaction is demonstrated in Figure 1, which shows separate regression lines for the posttest on the pretest, by treatment group. The lines show that the experimental group performed better on the posttest than did the control group, but that training was indeed most effective for participants with poor initial timing/rhythmicity.

Reading

Multivariate analysis of covariance (MANCOVA) was used to test the effect of IM training on the four measures of reading skill from the WJ-III ACH (Letter-Word Identification (LW-ID),

Table 2
Sequential Multiple Regression to Test Whether IM Training Was More Effective for Those with Initially High (Poor) Scores on Timing/Rhythmicity

Variables entered	ΔR^2	*p*
IM Pretest (centered), Treatment Group	.707	<.001
Pretest by group cross-product	.082	<.001

Reading Fluency, Passage Comprehension, and Word Attack). Pretest scores on these measures were used as covariates. As recommended by the test authors, *W* scores (a continuous, equal interval growth scale scores) were used for these analyses. The results of this analysis (and subsequent MANCOVA results) are summarized in Table 3. As shown in the table, the IM training did not demonstrate a statistically significant effect on reading achievement as measured by the WJ-III achievement tests.

Table 3 also shows the effects of IM training on measures of reading efficiency, TOWRE (Sight Word, Phonemic Decoding), and fluency, TSWRF. For this set of analyses, standard scores ($M = 100$, $SD = 15$) were used as both pre- and posttest scores; pretest scores and age were the

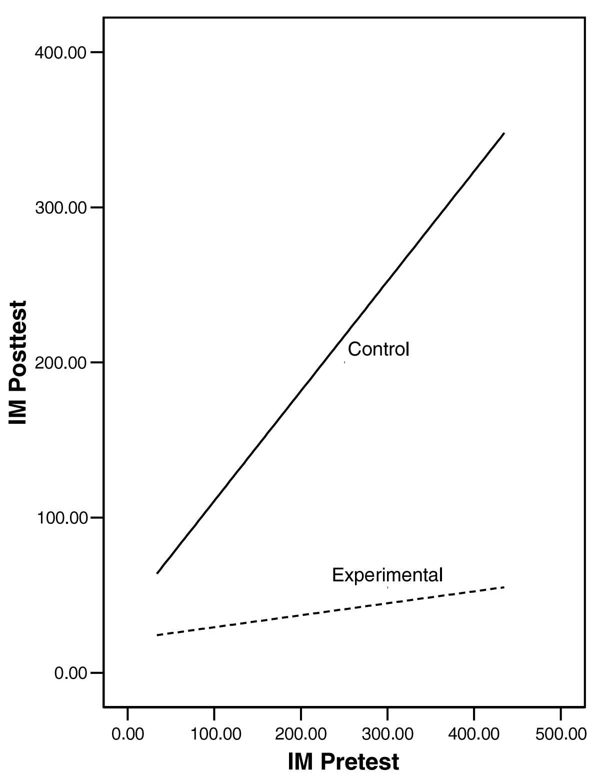

Figure 1. Interaction between IM pretest and IM training. The regression lines show that IM training was most effective in improving the timing and rhymicity of children with initial poor performance (low scores represent better performance).

Table 3
MANCOVA Results: Effect of IM Training on Reading

Measures	Hotelling's trace	$F(df)$	p	η^2
WJ Achievement Reading	.045	.842 (4, 75)	>.05	.043
Reading Efficiency & Fluency	.098	2.414 (3, 75)	.037	.089
CTOPP Phonological Processing	.205	3.899 (4, 76)	.003	.170

controlled variables. As shown in the table, the IM training produced a statistically significant effect on measures of reading efficiency and fluency. Participants who received IM training scored at a higher level on the multivariate dependent variable. The IM treatment accounted for 8.9% of the variance in reading efficiency and fluency, a small effect size (Keith, 2006, p. 508). Follow-up tests (univariate ANCOVAs) revealed a statistically significant effect for the TOWRE Sight Word Efficiency measure, $F(1,76) = 5.881$, $p = .009$, $\eta^2 = .072$, $g = .481$,[2] but not for the other measures.

Table 3 also shows the results of analyses of the IM effects on phonological processing skills as measured by the CTOPP (digit naming, letter naming, segmenting, and blending). Participants who received IM training demonstrated statistically significantly higher CTOPP scores, and the IM treatment accounted for 17% of the variance in CTOPP scores, a moderate effect. Univariate follow-up statistical analyses revealed statistically significant effects on the letter naming subtest, $F(1,79) = 8.680$, $p = .002$, $\eta^2 = .099$, $g = .536$, but not for the other components of the CTOPP.

Discussion

The current study employed a pre-/posttest evaluation design to investigate the effect of a specific SMT intervention (viz., Interactive Metronome) on reading performance in a sample of 86 first-, second-, third-, and fourth-grade students in a public charter school receiving Title 1 funding. Participants were randomly assigned to either an experimental (IM) or control group. The experimental group participated in a 3–4-week IM intervention designed to improve their timing/rhythmicity. The control group engaged in recess activities with nonparticipating classmates during each of the approximately 50 minute daily intervention sessions. All participants completed the same reading pre- and posttest measures, which were then analyzed via statistical methods that controlled for initial pretest performance levels and age (ANOCOVA, MANOVA).

Timing and Rhythmicity Treatment Findings

The results indicated that the IM treatment produced significant improvements in the timing and rhythmicity of elementary school students (as measured by the IM measurement system). The students in the IM treatment group, when compared to the control group, demonstrated statistically significant improvements, close to a two standard deviation increase in measured timing and rhythmicity scores.

IM treatment transfer effects were evaluated vis-à-vis pre-/posttest changes on standardized measures of reading achievement. The reading-dependent variables sampled four of the five reading skills identified as critical for early reading success by the National Reading Panel (2000). The

[2] We know of no formula for calculating Hedges' g for overall MANOVA results. Therefore, partial η^2 is reported for MANOVA results and both η^2 and g are reported for the univariate follow-up tests.

reading-dependent variables included standardized measures of phonics, phonological awareness, reading fluency, and comprehension. The fifth key reading skill, vocabulary, was not measured.

Before discussing the IM academic transfer effect findings, it is important to note this intervention did *not* include instruction or training of any kind in phonics, phonological awareness, and/or reading—this was *not* an *academic* intervention. The IM intervention is designed to improve participants' timing and rhythmicity through beeps, tones, tapping, and clapping. In other words, it would not be expected that participants in an intervention designed to improve timing and rhythmicity would demonstrate changes in reading achievement. Furthermore, the experimental IM treatment lasted approximately 3–4 weeks. Developmental *growth* curves based on nationally standardized reading tests (McGrew & Woodcock, 2001) suggest that similarly aged students (8.2 years) typically demonstrate little academic growth (as reflected by norm-referenced tests) over a 3–4-week period.

Reading Achievement Findings

Analysis of the individual reading tests indicated that the IM intervention produced significant transfer effects in phonics, phonological awareness, and reading fluency. Students in the IM experimental group demonstrated statistically significant improvement in their ability to *fluently* recognize familiar words within a *limited timeframe* (TOWRE test). In contrast, no significant treatment effect was demonstrated on an *untimed* word recognition measure (WJ-III LW-ID test). It is important to note that the primary difference between the TOWRE and WJ-III LW-ID tests is that of a *rate fluency* (TOWRE) versus *level* (WJ-III LW-ID) distinction. *Rate fluency* refers to the time taken to work from the beginning of a test to the end of a test. *Level* refers to the difficulty of an item or task (see Carroll, 1993).

Within the context of a rate-fluency/level-ability distinction, the current results suggest the hypothesis that although students did not *learn* to recognize more familiar words in isolation (i.e., their absolute word recognition *level* did not increase), they were able to recognize the words they previously *knew* faster (i.e., the fluency of their level of word recognition skills was improved). It appears that SMT-based IM treatments may demonstrate transfer effects on reading fluency/efficiency of existing word recognition skills, but not increase the overall level of word recognition skills in a student's repertoire.

The IM treatment group also demonstrated statistically significant pre- to posttest improvement accounting for 8.9% of the variance on an equally weighted multivariate reading composite measure (TOWRE and TSWRF). More impressive, however, was the posttest improvement accounting for 17% of the variance on a multivariate composite score that included the CTOPP tests Digit Naming, Letter Naming, Segmenting Nonwords, and Blending Nonwords and accounted for 9.9% of the variance on the CTOPP rapid automatized naming (RAN) test Letter Naming.

An alternative way to examine effect size is Hedges g (Howell, 2002). This statistic may be used to explain effect size as a percentage of growth, using a normal curve. Applying Hedge's g to the current results, the experimental group experienced a 20% growth on the CTOPP's RAN Letter Naming test and an 18% growth on the TOWER's Sight Word Efficiency. These growth rates compare favorably to the 15% growth identified in a meta-analysis of phonics instruction verses whole-word instruction conducted by the National Reading Panel's Committee on the Prevention of Reading Difficulties in Young Children (National Reading Panel, 2000).

The pre- to posttest reading achievement results suggest that improvements in timing and rhythmicity were associated with statistically significant improvements in three of the five major areas of measured reading: phonics, phonological awareness, and fluency. Yet, the results are not conclusive and must be moderated with a number of cautions. First, the experimental group did not demonstrate statistically significant increases on all the TOWRE's subtests. Second, although a significant improvement was observed on the CTOPP Letter Naming test, participants' performance on a similar test (Digit Naming) was not statistically significant. The key difference between the two tests is that the Letter Naming Test uses 26 letter stimuli, whereas the Digit Naming test's stimuli consist of 9 single-digit numbers. Third, on another measure of fluency (viz., WJ-III Reading Fluency) there was no statistically significant treatment effect. The lack of a significant effect for WJ-III Reading Fluency is at variance from a previous study involving high school students, wherein the experimental group demonstrated a statistically significant, 1-year grade level, improvement on the WJ-III Reading Fluency test (Taub, McGrew, & Lazarus, 2007).

Collectively, the current reading results suggest that students in the experimental IM treatment group demonstrated statistically significant improvements on more *fundamental* early reading skills (i.e., phonics and phonological awareness) and in their speed of processing basic lexical information (e.g., RAN for letters). However, with the exception of fluency of word recognition (i.e., Sight Word Efficiency test), students in the experimental group did not demonstrate statistically significant improvements at the single-word level.

Possible Causal Explanations: A Proposed Explanatory Framework and Preliminary Hypotheses

Previous IM intervention research reported statistically significant improvements in high schools students' performance on measures of reading recognition and reading fluency compared to a nontreatment control group (Taub, McGrew, & Lazarus, 2007). Similarly, IM-treated students with ADHD were reported to demonstrate statistically significant improvements in attention, reading, and language processing (Shaffer et al., 2001). This small collection of academically related studies, investigating direct reading achievement indicators and behaviors that exert an indirect causal influence on achievement (i.e., attention and concentration), are intriguing and suggest the need to focus efforts on understanding *why* improvements in timing and rhythmicity (via SMT interventions) display such far-point transfer effects.

In an effort to jump start efforts directed at understanding the underlying SMT–academic causal mechanisms, it is proposed that SMT-based research needs to be placed in a theoretically sound and empirically based research/conceptual framework. Furthermore, it is argued that the observed positive cross-domain or domain-general effect of SMT-based interventions result from improvements/changes within a domain-general cognitive mechanism (or a small number of domain-general mechanisms). Based on a review of relevant mental interval timekeeping literature, the following preliminary hypotheses are offered.

Master Internal Clock Based on Scalar Timing Theory

To deal with time, organisms (animal and human) have developed multiple timing systems that are active in more than 10 orders of magnitude with various degrees of precision (Buhusi & Meck, 2005). According to Buhusi and Meck, humans have developed three general classes of timing systems (circadian, interval, and millisecond timing), each associated with different behaviors and brain structures/mechanisms. The millisecond timing system, which is involved in a number of classes of human behavior (e.g., speech, music, motor control) and that primarily involves the brain structures of the cerebellum, basal ganglia, and the dorsolateral prefrontal cortex (Buhusi & Meck, 2005; Lewis & Miall, 2006), is most relevant for understanding SMT-based interventions.

Pacemaker-accumulator model. Human behavior based on the perception and timing in the range of seconds to minutes has traditionally been explained by the predominant model of interval timekeeping, namely, the *pacemaker–accumulator model* (PAM). The PAM, which is based on the *scalar expectancy or timing theory* (Church, 1984; Gibbon, Church, & Meck, 1984; Meck, 1983), "is relatively straightforward, and provides powerful explanations of both behavioral and physiological data" (Buhusi & Meck, 2005, p. 755).

Briefly, the 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?").

Given evidence that supports a domain-general master internal clock central to many complex human behaviors (see Buhusi & Meck, 2005; Lewis & Miall, 2006), it is suggested that the *master internal clock* may be the mechanism that mediates SMT performance and intervention effects. It is hypothesized that SMT training improves human performance across a number of domains (e.g., reading and ADHD) via an increase in the *clock speed* of the master internal clock.

It is beyond the scope of the current study to describe the specific hypothesized brain mechanisms that produce a higher *clock speed* for the internal master clock. What is important to note in the current context is that mental interval timekeeping and temporal processing research has suggested that a *higher mental clock rate* enables individuals to perform specific sequences of mental operations faster and reduces the probability of interfering incidents (i.e., less disinhibition). These two conditions produce superior performance on cognitive tasks as well as more efficient basic information processing skills (Rammsayer & Brandler, in press).

The Master Mental Clock and Cognitive/Neuropsychological Constructs

The major components of PAM-based mental interval timekeeping have strong similarities to a number of domain-general cognitive mechanisms featured in contemporary cognitive information processing and/or neuropsychological research. Working memory, which is pivitol to PAM, is a central concept in major models of information processing. In addition, the PAM long-term (Buhusi & Meck, 2005) memory likely invokes early stages of memory consolidation in long-term memory or storage, another major component of information processing models of cognition. Furthermore, the *if-then* decision-making function of the PAM *comparator* is a function typically associated with skills involved with executive functioning (e.g., monitor, evaluate, change). Finally, research has implicated the important role of *attention* during the cognitively controlled portions of interval timing (Buhusi & Meck, 2005). Therefore, it is hypothesized that a conceptual cross-walk between the major components of the PAM master internal clock and contemporary cognitive information processing theories suggests that SMT performance and SMT transfer effects result in an increased efficiency in the functioning of the domain-general cognitive information processing mechanisms of (a) working memory, (b) executive functioning, and/or (c) controlled or executive attention.

Working Memory, Executive Functioning, and Executive Controlled Attention

Executive functioning (EF), which is also frequently called the *central executive system*, is a term used for a broad construct that represents a cluster of skills necessary for efficient and successful goal-directed behavior (Welsh, 2001). The EF constructs of planning, monitoring, inhibituation, and attention/concentration, elicit a range of basic cognitive processes (e.g., attention, perception, language, and memory) that are coordinated for a very specific purpose: subserving goal-directed behavior.

EF processes are believed to work in symphony to facilitate goal-directed task completion. Timing and processes related to mental timing are believed to be a component of executive function (Welsh, 2001), as is the utilization of executive functions during reading performance (Bull & Scerif, 2001). Because EF is an integration of a constellation of abilities necessary for the planning, self-monitoring/regulating, and evaluation of successful task completion, the area of self-regulated learning has received considerable attention with regard to a variety of cognitive activities (e.g., meta-cognition, pre-attentive processes, sluggish attentional shifting, specific strategy selection and implementation, inhibition, multitasking activities, task switching, maintenance of information under conditions of interference, and resistance to interference; Bull & Scerif, 2001; Borkowski, Carr, & Pressley, 1987; Kane, Bleckley, & Conway, 2001). The central role of EF in the enhancement of selective or controlled attention, the ability to switch between plans and strategies, and the inhibition of task-irrelevant information (intrusions) in working memory (Engle, Tuholski, Laughlin, & Conway, 1999; Passolunghi & Siegel, 2004) is consistent with theoretical and descriptive interpretations of SMT and interval time tracking models.

It is proposed that the *executive controlled attention model* of working memory (Engle, Kane, & Tuholski, 1999; Kane, Bleckley, Conway & Engle, 2001), which invokes the EF system, should be entertained as a potentially useful initial model to explain the domain-general effects of SMT-based interventions. Briefly, the executive controlled attention working memory model hypothesizes that individual differences in task performance are related to EF *controlled attention*. This means that individuals with higher working memory demonstrate better (or more efficient) use of attentional resources and are more able to resist interference during the encoding and retrieval processes than individuals with lower working memory. It is our hypothesis that SMT training does not improve working memory by increasing capacity, rather that SMT training may result in more *efficient* use of an individual's working memory system. The central role that the *general* capability to *efficiently process* information plays in task performance is consistent with a general mechanism explanation for the diversity of across-domain effects of SMT training. Central to the controlled attention working memory model is the role of EF. The alternative working memory view, which argues more for emphasis on underlying *modality-specific* working memory subprocesses (Palladino, Mammarella, & Vecchi, 2003), in contrast to resource-sharing models, presents a much more complex alternative model by which to explain positive SMT training effects across such diverse performance tasks (although it would be inappropriate to completely discard it as a possible explanation at this time). The search for a domain-general mechanism to explain SMT generalized training effects, such as the controlled attention working memory model, represents a more parsimonious approach that is believed to be preferred as formative attempts are made to describe and explain SMT training effects.

Finally, the recent suggestion that *g* or general intelligence (the most enduring and robust domain-general cognitive mechanism in the history of the psychometric study of intelligence) may be more a function of *temporal processing* and not necessarily reaction time (as measured by the traditional Hick paradigm; Rammsayer & Brandler, in press) suggests that mental interval timekeeping models (e.g, PAM) may describe and explain a primary elementary cognitive mechanism involved in most all complex human behavior. If *temporal g* exists, then the across-domain positive treatment effects of SMT training might be explained as the improvement of general neural efficiency via greater resolution of the temporal *g* internal clock.

Summary

This study investigated the effect of a SMT training intervention on elementary-school-age students' reading achievement. The observance of statistically significant improvements in the experimental group's performance on posttest measures of reading, when compared to the control group, is impressive given the nature of the *nonacademic* intervention. Yet, the results are not conclusive and are inconsistent in some cases. For example, the elementary school students scored significantly better on a timed single word recognition test, yet, there was no significant between-group difference on a measure that required reading short simple sentences (WJ-III Reading Fluency). Also, previous research with high school students reported a statistically significant relationship between SMT improvements and reading fluency. One possible explanation for the divergent developmental intervention effect findings is that elementary school students are *learning how to read*, whereas high school students are *reading to learn*. In other words, high school students have mastered or automatized their reading skills, whereas the elementary school students are learning how to read.

Nevertheless, the automatization of critical early reading skills (viz., phonics, phonological awareness skills, and RAN performance), which emerge primarily during the early school grades, are the specific areas where the elementary-aged experimental participants demonstrated the most significant improvements in the current study. It is also possible that studies (the current study, inclusive) that have reported improvements in timing and rhythmicity over short periods (3–4 weeks) may only demonstrate significant effects on the processing of overlearned (automatized) information, in contrast to the more deliberate or controlled learning of new information. This may also explain why golfers, who presumably have overlearned their golf swing, become more accurate with improvements in timing/rhythmicity.

It is believed that subcomponents of the constellation of executive functioning are effected by SMT interventions. Because of the cross-domain influence of working memory on task completion, the executive controlled attention model of working memory, which is heavily dependent on the executive functioning system, was hypothesized as a potentially useful model for conceptualizing SMT research and for interpreting research findings. The executive controlled aspect of working memory was suggested as a possible general cognitive mechanism responsible for the observed positive influence of SMT training across such diverse domains as academics, athletics, and attention/concentration.

Limitations and Future Research

This study may be limited by participants' parents self-selection to have their child attend a public charter school receiving Title 1 funding. Participants may also have been more similar on several demographic variables (e.g., ethnicity, socioeconomic status) than would be found in public school settings.

Because of the relatively small sample size it was not possible to make a distinction between students receiving special education services and those who were not. It is recommended that future studies examine this difference as well as investigate differential SMT training effects with regular education students experiencing academic difficulties. It is also recommended that future studies investigate SMT training effects with students who were unable to graduate or progress to the next grade level because they did not reach a threshold score on high-stakes tests of academic achievement.

Finally, in the present study posttests were administered immediately after SMT training; therefore the stability of the observed positive effects of SMT training on the academic achievement dependent variables is not known. It is recommended that future studies investigate the consistency of the observed positive effects of SMT training on academic achievement over an extended period.

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