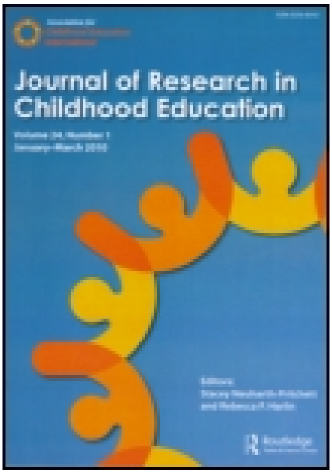

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Effects of Improvements in Interval Timing on the Mathematics Achievement of Elementary School Students

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This article examines the effect of improvements in timing/rhythmicity on mathematics achievement. A total of 86 participants attending 1st through 4th grades completed pre- and posttest measures of mathematics achievement from the Woodcock-Johnson III Tests of Achievement. Students in the experimental group participated in a 4-week intervention designed to improve their timing/rhythmicity by reducing latency response to a synchronized metronome beat. The intervention required, on average, 18 daily sessions of approximately 50 minutes each. The results from this nonacademic intervention indicate the experimental group's posttest scores on the measures of mathematics were significantly higher than the nontreatment control group's scores. This article proposes an integration of psychometric theory and contemporary information processing theory to provide a context from which to develop preliminary hypotheses to explain how a nonacademic intervention designed to improve timing/rhythmicity can demonstrate a statistically significant effect on students' mathematics achievement scores.

Keywords: early childhood mathematics, achievement, assessment, educational intervention, mathematics, elementary, intervention, standardized tests

Mathematics competency is crucial to success in academic and real-world environments. The skills necessary for mathematical success in K-12 schools include number correspondence, addition, subtraction, problem solving, and fluency (Mullis et al., 2001; Rivera-Batiz, 1992; Rourke & Conway, 1997). With the exception of simple arithmetic (Bull & Johnston, 1997; Bull, Johnston, & Roy, 1999; Geary, 1993; Rourke & Conway, 1997), relatively little is known about the development of mathematics skills and/or the underlying cognitive abilities that contribute to mathematics achievement and performance.

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Research examining the cognitive processes involved in mathematics performance has typically reported laboratory-based, domain-specific investigations of the basic cognitive tasks and strategies individuals use to solve mathematical problems (Ashcraft, 1995; Geary, 1994). The domains typically investigated have included the development of number sense (i.e., the implicit awareness of quantitative concepts and relationships; Berch, 2005; Fuchs et al., 2010; Gersten & Chard, 1999), the development of algorithms (Geary, 1993), and other domain-specific competencies necessary for arithmetical success (Bryant & Rivera, 1997; Hoard, Geary, & Hamson, 1999).

The state-of-the-art of mathematics performance research has recently benefited from an expanded focus on the breadth of psychometric (cognitive) constructs included in research studies (e.g., Bull & Johnston, 1997; Bull et al., 1999; Geary, 2007; Geary et al., 2009; Geary, Hoard, Nugent, & Bailey, 2012) and the marriage of psychometric and information-processing (IP) theories (Geary, 2007). It is our position that integrating research involving psychometric and IP theories may advance our understanding of students' academic (e.g., mathematical) achievement.

Integrating our understanding of academic performance behavior with academic performance process at a psychological level (i.e., neuroscience or neuropsychological interventions) may be the next frontier for research in academic performance. One neuroscience-based intervention, the use of synchronized metronome tapping (SMT), has received significant attention in empirical research.

Several behaviors important to school success (e.g., academic achievement, attention, motor planning, and sequencing) have demonstrated statistically significant relationships with timing/rhythm (Barkley, 1997a, 1997b; Greenspan, 1992; Wolff, 2002; Wolff, Michel, Ovrut, & Drake, 1990) as well as areas of academic achievement (e.g., language, mathematics, reading, and overall academic achievement; Ellis, 1992; Mitchell, 1994; Weikart, Schweinhart, & Larner, 1987).

A number of recent studies that used the Interactive Metronome (IM), an SMT-based intervention, have demonstrated positive impacts on school-age children's reading. Taub, McGrew, and Keith (2007) found that elementary school-age students in the experimental IM group experienced statistically significant gains in phonics, phonological processing, and reading fluency, when compared to a nontreatment control group. Ritter, Colson, and Park (2013) reported that elementary school-age participants in an combined integrated language and IM treatment condition demonstrated greater gains in reading fluency and comprehension than gains reported for the integrated language program alone. SMT is also believed to play an important role in the diagnosis of students with disabilities and developmental dyslexia (Wolff, 2002). Specifically, students experiencing dyslexia were found to have a difference of 100 to 150 milliseconds when responding to a metronome beat when compared to students not experiencing a learning disability, thus indicating that a deficit of temporal IP may underlie or contribute to dyslexia (Wolff, 2002).

The purpose of this study was to investigate the effects of an SMT-based intervention on the mathematics achievement of elementary school-age students. We first begin with an overview of contemporary literature on IP models and mathematics. IP and executive functions are believed to be the primary neurological mechanisms affected by SMT interventions. This is followed by a review of the literature on mathematics achievement and working memory and timing/rhythm-based research.

IP MODELS AND MATHEMATICS ACHIEVEMENT

IP Models Defined

The recent integration of psychometric research with contemporary IP theories has resulted in a better understanding of cognitive and academic performance (Kyllonen, 1996; McGrew, 2005). Although slightly different IP models are the subject of empirical investigation, the four-source consensus model (Kyllonen, 1996) is used here. Within Kyllonen's (1996) model, the four primary components contributing to IP performance are procedural knowledge, declarative knowledge, processing speed, and working memory.[1] Of the four, working memory is likely the most important component when integrating psychometric and IP models to explain academic performance. Working memory plays a central role in the explanation of individual differences in (1) language comprehension (Engle, Cantor, & Carullo, 1992; Just & Carpenter, 1992), (2) reading and mathematics performance (Geary, 2007; Hitch, Towse, & Hutton, 2001; Leather & Henry, 1994), (3) reasoning or general intelligence (Ackerman, Beier, & Boyle, 2002; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Fry & Hale, 1996, 2000; Kyllonen & Christal, 1990; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002), and (4) long-term memory performance (Park, Smith, Lautenschlager, & Earles, 1996; Süß et al., 2002).

The theoretical explanations for the consistently strong working memory→criterion relations differ primarily in the cognitive resources proposed to underlie working memory performance (Lohman, 2000). A sample of resources hypothesized to influence cognitive/academic performance vis-à-vis working memory are storage capacity, processing efficiency, the central executive, domain-specific processes, and controlled attention (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Engle, 2002; Engle et al., 1999). Researchers have hypothesized that working memory is strongly associated with complex cognitive performances (e.g., fluid reasoning, reading, and mathematics) because of the considerable amount of information that must be actively maintained within the limited resources of working memory (Baddeley, 2012; Engle, 2002; Unsworth & Engle, 2007). This is most evident when active transformation of the information in working memory, which requires considerable focused controlled attention, is required.

The important conclusion from this literature is that contemporary psychometric and IP research converge on the critical importance of working memory in a wide variety of cognitive/academic performance domains, including mathematics. These results highlight the importance of increasing our understanding of the relationship between select psychometric/IP cognitive constructs (working memory in particular) and mathematics achievement.

IP Models and Mathematics Performance Research

IP research has consistently suggested a significant causal relationship between working memory and mathematics performance (Geary, 1993, 2007; Passolunghi & Siegel, 2004). Several authors have reported that working memory plays a crucial role in calculation and in solving arithmetic word problems (Furst & Hitch, 2000; Geary, 1993; Geary, Hamson, & Hoard, 2000; McLean & Hitch, 1999; Passolunghi, Cornoldi, & De Liberto, 1999; Passolunghi & Pazzaglia, 2004; Passolunghi & Siegel, 2004; Swanson, 1993).

The central executive function component of Baddeley's (1996) domain-general working memory system is hypothesized to allow for improvement in performance via the enhancement of selective or controlled attention. Controlled attention can be defined as the flexibility to switch between retrieval plans as well as the inhibition of task-irrelevant information (intrusions) in working memory (Engle, 2002; Engle et al., 1999; Passolunghi & Siegel, 2004). For example, computational word problems require the ability to reduce the accessibility of memories of nontarget and irrelevant information, which often can produce "intrusion errors" (Passolunghi & Siegel, 2004). To adequately construct a representation of math word problems, information must be examined for relevance, selected or inhibited, and then integrated with other information (Passolunghi et al., 1999; Passolunghi & Pazzaglia, 2004). Barrouillet, Fayol, and Lathulière (1997) have noted that even during the most elementary math operations (e.g., association of two operands with a response) a number of incorrect response competitors are activated and must be inhibited (Geary, 1993; Geary et al., 2000).

In addition to working memory, processing speed has been implicated in efficient performance across cognitive and academic performance domains (Kail, 1991; Kail, Hall, & Caskey, 1999; Lohman, 1989). A pivotal concept in IP models is that human cognition is constrained by a limited amount of processing resources, particularly in working memory capacity. Many cognitive activities require a person's deliberate effort; however, people are limited in mental capacity and in the amount of mental effort they can allocate to a specific activity. In the face of limited processing resources, speed of processing becomes critical because processing speed determines, in part, how rapidly limited resources can be reallocated to other cognitive tasks (Kail, 1991). This is why processing speed is implicated as a determinant in efficient working memory processing, including in the fluency of retrieval of numerical information from long-term memory (Case & Toronto, 1982). It is widely accepted that working memory is an important IP component for complex cognitive and academic performance (e.g., mathematics). However, intervention-based research designed to improve working memory performance is limited, as is research investigating the effects of interventions/treatments to improve academic achievement indirectly through improved IP performance.

WORKING MEMORY—IP—MENTAL/INTERVAL TIMING—MATHEMATICS LINK?

We believe that a potentially important (and often overlooked) historical psychometric/IP link may exist that could account for the importance of working memory in mathematics and other cognitive performance situations. According to Stankov (2000), one of the earliest recorded descriptions of a psychometric factor that captures a critical essence of working memory is the temporal tracking ability (Stankov, Horn, & Roy, 1980).

More recently, cognitive psychology has extended research into temporal tracking to include the phenomenon of interval and millisecond-level timing. Research indicates humans have developed multiple timing systems that are active over more than 10 orders of magnitude, which are generally categorized into three broad groups that involve different neural mechanisms (Buhusi & Meck, 2005). Circadian timing operates over the 24-hour sleep–wake cycle. Interval timing covers human behaviors governed in terms of seconds to minutes, such as decision making and deliberate time estimation. Millisecond timing is the most precise and plays a crucial role in motor behaviors, playing music, speech recognition and generation, dancing, and many cognitive mechanisms associated with intelligence (Buhusi & Meck, 2005).

Interval and millisecond timing has been studied through a variety of research paradigms. Among the oldest are tasks that require an individual to maintain synchrony with auditory tones (e.g., from a metronome; see Wing & Kristofferson, 1973). As an example, SMT requires participants to replicate, through movement, the beat of a metronome. A central component of contemporary SMT methods is the provision of visual and auditory feedback that reflects the degree to which the person's "on-target" tapping approximates the target stimulus as measured in milliseconds. SMT is described as a linear error correction mechanism, which compensates for asynchronies by locally adjusting the phase of the underlying timekeeper (Vorberg & Fuchs, 2004).

When temporal deviations from the underlying metronome-based interval are realized (e.g., via visual and/or auditory performance feedback measured in milliseconds) an automatic phase adjustment is triggered. The allocation of attentional resources and the inhibition of task-irrelevant stimuli, which may divert cognitive processing resources away from timing, are hypothesized to play a significant role in metronome-based synchronization of rhythmic movements (Brown & Bennett, 2002). In addition, the quickness and efficiency of the phase adjustment mechanism is believed to eliminate the necessity for long-term memory or learning (Vorberg & Fuchs, 2004). Thus, it is reasonable to hypothesize that synchronizing rhythmic movements to a metronome occurs primarily within the short-term, immediate resource-limited cognitive mechanism of working memory, which requires temporal tracking ability and controlled attention.

The study of the cognitive processes involved in the temporal control of simple rhythmic movements has been dominated largely by two different theoretical frameworks. One is the linear, stochastic representational mental time/interval-keeper models (Engbert et al., 1997; Krampe, Engbert, & Kliegl, 2002). The other is the dynamic systems frameworks (i.e., nonlinear oscillator models; Engbert et al., 1997; Krampe et al., 2002) or sensory-motor theories of temporal representation (i.e., temporal tracking as a form of sensory-guided action that uses the sensory-memory image to drive a movement via a control mechanism).

The mental-timekeeper models, as represented by the pacemaker-accumulator model (PAM), have been the dominant models for explaining timing-related human behaviors, but even PAM has not settled on whether there is a single pacemaker, multiple dependent pacemakers, or multiple independent pacemakers (van Rijn & Taatgen, 2008). Despite the lack of a consensus regarding the theoretical basis and precise neural mechanisms of interval and millisecond timing, there is extensive research suggesting that temporal processing (i.e., a human brain clock) is fundamental to many human motor and cognitive behaviors (Buhusi & Meck, 2005; Mauk & Buonomano, 2004) and is central to understanding SMT interventions.

Timing/Rhythm and Academic Achievement

A primary working hypothesis in this investigation is that research across different cognitive psychology subdisciplines has identified important links between central theoretical cognitive constructs and a variety of human performance outcomes (e.g., academics). It is our opinion that much of this research may be focusing on related, if not the same, cognitive constructs, many of which are important for mathematical success. Working memory has clearly been identified as a central theoretical explanatory construct for many complex cognitive performances. Temporal tracking and temporal processing may represent an important facilitator of human cognitive performance that occurs within the IP subcomponent, working memory. The advancement of this hypothesis comes from recent studies demonstrating that SMT-based interventions focusing on improving the ability to judge and maintain rhythmicity (such as interventions involving temporal or mental time-keeping or tracking) produced improvements across a diverse array of outcome domains (McGrew, 2013).

Several behaviors important to school success demonstrated statistically significant relationships with timing/rhythm, including academic achievement, attention, motor planning, and sequencing (Barkley, 1997a, 1997b; Greenspan, 1992; Wolff, 2002; Wolff et al., 1990). Areas of academic achievement reported to be affected by timing/rhythm included language, mathematics, reading, and overall academic achievement (Ellis, 1992; Mitchell, 1994; Weikart et al., 1987).

Recent research has also highlighted the potentially important role of timing precision and rhythm in the diagnosis of students with disabilities and developmental dyslexia (Wolff, 2002). Typically, children are able to tap their finger, repeat a beat, or repeat a single syllable within about 50 milliseconds on either side of a pacing signal (Fraisse, 1982; Poeppel, Ruhnau, Schill, & Steinbuechel, 1990). In contrast, students with dyslexia have a latency of anticipation of a metronome beat in the range of 150 to 200 milliseconds (Wolff, 2002). This finding led Wolff to hypothesize that an underlying deficit of temporal IP may contribute to dyslexia.

More recently, Taub et al. (2007) reported a statistically significant effect for improvement in timing/rhythmicity on a number of reading achievement outcomes, including reading decoding, reading fluency, and rapid automatized naming. This study used an SMT-based assessment and intervention technique called the IM method to improve participants' latency response to a reoccurring metronome beat. Ritter et al. (2013) found that IM treatment, combined with an integrated language training program, produced greater reading fluency and comprehension gains than the integrated language-only treatment. Other studies using the IM method report significant effects for improvements in golf accuracy (Libkuman & Otani, 2002; Sommer & Rönnqvist, 2009), attention, motor control, language processing, and decreased aggressive behavior in children with attention-deficit/hyperactivity disorder (ADHD) (Shaffer et al., 2001). Interestingly, McGowan, Lin, Ou-Yang, Zei, and Brobman (2012) found that greater concentration, as measured by IM millisecond performance, resulted in shorter birth labor in nulliparous women.

Collectively, these diverse studies indicate that improvements in the latency response (measured in milliseconds from the target tone or beat) to a recurring metronome-based intervention, which is hypothesized to improve mental/interval/temporal tracking within the working memory system, possibly via increased attentional control, may produce domain general effects across a number of human performance domains. More specifically, and most relevant to the present study, is the area of mathematics.

PURPOSE

The cross-domain effects of SMT-based assessment and intervention argues for further investigation. The purpose of this article is to investigate the effect of the SMT method on mathematics achievement.

METHOD

Participants

Study participants attended an inner-city charter school. The main difference between a charter school and a public school is the charter school receives funding directly from the State of Florida. The school provides education to students between kindergarten and 5th grade. Approximately 83% of the students attending the school received free or reduced-price lunch; all of the participants in the study were of African American descent. Study participants attended 1st through 4th grades and ranged from age 7 to 10 years with a mean of 8.15 years ($SD = 10$). Parents of all participants signed a parent permission form and participants provided both verbal and written assent to participate.

Pre–Post Dependent Variable Measures

The Woodcock-Johnson Tests of Achievement III (WJ III; Woodcock, McGrew, & Mather, 2001) served as a pre- and posttest measure of participants' mathematics achievement. As described in the WJ III technical manual (McGrew & Woodcock, 2001), the entire WJ III sample was stratified according to race, gender, geographic region, education, and age to mirror the population characteristics of the U.S. Census projections for the year 2000. The entire WJ III was standardized on 8,818 individuals.

All participants completed the two tests of mathematics (the Calculation and Math Fluency tests) from the WJ III that contribute to the Math Calculation Skills cluster. The Calculation test measures mathematics computation skills by requiring examinees to write numbers and to complete basic to complex mathematical operations. The Math Fluency test is a measure of automaticity of basic mathematics calculation skills and requires examinees to complete a combination of simple addition, subtraction, and multiplication problems within a 3-minute period.

STM Treatment

The SMT-based assessment intervention system used in the study was the IM method, hereafter referred to as IM. The goal of training using the IM is to reduce the mean negative synchronization error during normal tracking of a regularly occurring metronome beat. During IM training, the participant receives auditory and visual feedback. However, the auditory feedback guidance system is the primary feedback method. This system provides the participant with tonal stimuli (i.e., a short beep) that indicates whether the participant responded prior to, at, or past the regularly occurring auditory metronome beat, which is presented through headphones. The IM method uses computer software that measures, in milliseconds, the accuracy of participants' expectancy response to the metronome beat. Participants are presented with different tonal stimuli (i.e., a beep) depending on whether their expectancy response (generally a hand clap) was far from, close to, or at the metronome beat. In addition to the auditory guidance system, a visual output of the latency of their response is provided on a computer screen (similar to a digital clock).

The goal of IM training is the improvement of participants' timing/rhythmicity through the reduction in the millisecond latency between the occurrence of the regularly occurring metronome beat and the participant's physical expectancy response (generally a clapping response) indicating their expectation of the recurrence of the beat. IM training requires 15 to 18 hours of treatment. At the end of training, participants typically responded within approximately 15 milliseconds on either side of the beat. Prior to training, a participant's initial latency response is typically 80 to 100 milliseconds on either side of the beat. A typical IM training protocol engages participants in approximately 25,000 motoric repetitions. These physical responses, which indicate participants' expectancy of the onset of the recurring metronome beat, require several physical movements, including clapping hand-to-hand with a sensor on one palm, tapping the palm sensor lightly on the thigh, and tapping floor sensors with either the toe or back of the foot.

Procedure

All participants were randomly assigned to either an experimental or control group after they completed the WJ III mathematics pretest. A total of 49 participants were in the treatment group and 37 participants were in the control group. Participants in the experimental group were divided into four grade-level groups. Each group ranged in size from seven to 12 participants. The students in the experimental group participated in 18 daily sessions over a 4-week period. Each session lasted approximately 50 minutes. To ensure the IM protocol was followed, the first two authors randomly observed the treatment sessions. Although the experimental group participated in the intervention, the control group and nonstudy participants were in recess.

Immediately after the experimental group completed the IM intervention (approximately 4 weeks after the pretest administration), the selected WJ III math pretests were again administered to all participants. Participants from the experimental and control groups completed all tests together (small-group testing). The pre- and posttest administrations were completed in the students' own classrooms. All tests were administered by graduate students who had completed or were near the end of their second semester of graduate training in the administration of standardized tests. The lead author supervised all pre- and posttest administrations. The second author, who is coauthor of the WJ III, was present during random pre- and posttest sessions to ensure that standardized test administration procedures were followed. Graduate students serving as test administrators were unaware of each student's group assignment. Standardized administration procedures were followed during the administration of each test, with the exception that the tests were administered in groups, rather than individually. Although administered in groups, several steps were followed to ensure that standardized test administration procedures were followed as closely as possible. These steps included (1) the first author was present during all group administrations, (2) students were tested in groups with a minimum ratio of one test administrator to four students during all group administrations, (3) a coauthor of the WJ-III who confirmed that group administration of the selected tests would not compromise standardized test administration was present during random pre- and posttest sessions, and (4) all students progressed through the group test administration at the same time. If a student did not accurately complete a sample item, the group administration was stopped and the graduate student administering the tests followed standardized administration procedures to ensure adequate completion of the sample item.

TABLE 1
ANCOVA Results: Effect of Synchronized Metronome Tapping Training on Mathematics

Measures	*F*	*df*	*p*	η^2	*Hedges g*
Calculation	4.821	1, 82	.016	.056	.293
Math fluency	3.304	1, 82	.037	.039	.246

RESULTS

This study investigated the effect of the IM intervention on mathematics achievement. Participants' pre- and posttest scores were obtained from the administration of two WJ III mathematics tests. The IM method was used to measure and improve participants' latency response to a synchronized metronome beat. Multivariate analysis of covariance (MANCOVA) was the primary method of analysis, with univariate ANCOVA follow-up tests used for all analyses. To control for the effect of initial level of performance on the subsequent posttests, participants' W scores on the WJ III pretest measures of mathematics served as the covariate(s) in all analyses. Given the prediction that statistically significant differences would favor the experimental group, one-tailed tests ($\alpha = .05$) were used to evaluate statistical significance.

Participants who received the IM training showed statistically significantly higher scores on the multivariate Math posttest (controlling for the Math pretests) compared to the control group participants, $F(1, 81) = 3.667$, $p < .015$, although the effect size was relatively small (${\eta_p}^2 = .083$). Table 1 presents the results of the univariate follow-up tests, which revealed statistically significant effects for both measures of math skills: Calculation ($p = .016$, $\eta^2 = .056$, $g = .293$) and Math Fluency ($p = .037$, $\eta^2 = .039$, $g = .246$).

DISCUSSION

The purpose of this study was to determine if a short-term, nonacademic STM treatment, designed to improve the timing/rhythmicity abilities of elementary school-age students, would generalize to increased performance in mathematics achievement test scores. This study included 86 participants attending either 1st, 2nd, 3rd, or 4th grade in an inner-city charter school. Participants were randomly assigned to either an experimental group or a control group. The IM method, an SMT-based intervention, was used to improve the experimental group's timing/rhythmicity during 18 separate 50-minute daily SMT intervention treatment sessions. Although the participants in the experimental group received the IM intervention, participants in the control group were in recess. Neither group received academic instruction during the IM treatments. Pre- and posttest performance on two WJ III mathematics achievement tests (Calculation and Math Fluency) was the dependent variable. The ANCOVA statistical procedure was used to analyze all scores, with the participants' pretest mathematics scores serving as the covariant (to control for regression to the mean pre–post test effects).

The results indicated that the SMT method had, on average, a statistically significant effect on the experimental participants' math achievement scores, above and beyond the typically expected growth demonstrated on math achievement during the same time frame (i.e., the change in math scores for the control group subjects). As measured by the WJ III Calculation and Math Fluency tests, participants in the experimental group were found to have completed, on average, more mathematics problems, were more accurate in their math problem solving, and completed the mathematics problems faster than the control group.

Although IM training had a statistically significant effect on mathematic achievement scores, the magnitude of the effect was small and accounted for approximately 8% of the variance in the test scores. An alternative way to examine effect size is through Hedges *g* (Howell, 2002). Table 1 presents the effect size for Hedges *g* on Math Calculation and Math Fluency. This statistic may be used to explain effect size as a percentage of growth, using the normal curve distribution. Using this conversion of Hedge's *g*, we found that when compared to the control group, the experimental group experienced a 12% growth on the Calculation test and a 12% growth on the Math Fluency test, when compared to the control groups. These growth rates also compare favorably to the 15% growth, using Hedges *g*, identified in a meta-analysis of phonics instruction conducted by the National Reading Panel's Committee on the Prevention of Reading Difficulties in Young Children (National Reading Panel, 2000). Developmental growth curves based on nationally standardized mathematics tests (McGrew & Woodcock, 2001) suggest that students of similar age (8.15 years) typically demonstrate little academic growth (as reflected by norm-referenced tests) over a 3- to 4-week period. The detection of significant changes in math achievement scores from a nonacademic intervention after only about 4 weeks and 18 intervention sessions lasting about 50 minutes each is, at a minimum, a significant finding for an initial pilot study and is worthy of further exploration.

Preliminary Working Hypothesis and Areas to Investigate

Cognitive and intelligence researchers have long sought for (and argued about) the "holy grail" of intelligence—an underlying core essence or mechanism that plays a role in most all intellectual and human performance situations. It is typically referred to as *g*, or general intelligence. The general consensus touches on the concept of neural efficiency (Jenson, 1998). Such a general mechanism or process is considered a domain-general cognitive mechanism, as it works across multiple domains of human ability. Some have referred to such general mechanisms as a "jack-of-all-trade" cognitive mechanism (Chiappe & MacDonald, 2005; Rakison & Yermolayeva, 2011). This contrasts with domain-specific cognitive mechanisms, which are compartmentalized (modular), brain-based components with limited generalization or transfer effects after training.

In addition to the present positive results, previous studies have reported significant effects linking mental time-keeping and academic achievement (e.g., Buhusi & Meck, 2005; Ritter et al., 2013; Taub et al., 2007), dyslexia (McGee, Brodeur, & Symons, 2004; Wolff, 2002), golf performance (Libkuman & Otani, 2002; Sommer & Rönnqvist, 2009), attention, motor control, language processing, reading (Taub et al., 2007), and parent report of regulation of aggressive behavior Shaffer et al. (2001). We believe that, collectively, such cross-domain findings suggest SMT-based interventions must be modifying a domain-general cognitive mechanism.

Via task analysis of IM-based SMT training, we offer the hypothesis that the primary mechanism by which working memory is enhanced is the training of controlled attention and inhibition. To stay "on target" requires the subject to focus like a laser on the target tone (for sustained periods of time) and to shut down or inhibit attention to external or internal (mind-wandering) stimuli. Attentional capture is minimized by the process of inhibition (ignoring task irrelevant distractions—self-generated random thoughts or "mind wandering"). The constant millisecond-based feedback requires participants to suppress attending to distracting external and internal stimuli. The participants' personal mind manager (i.e., executive functions) must constantly monitor the feedback and update immediate working memory so the participants can adjust and correct their synchronization on a real-time basis. Inhibition, shifting, and updating are the three primary cognitive processes believed to be involved in each person's personal mind manager—collectively referred to as the "executive functions" of the brain (Friedman et al., 2008).

The benefit of SMT intervention methods, which focus primarily on maintaining and judging rhythm to a target tone with constant millisecond-based accuracy, may be the enhancement of the domain-general construct of working memory, which, in turn, is strongly related to executive attention and attentional and inhibitory control (Chun, Golomb, & Turk-Browne, 2011; Engle, 2002; Eysenck & Derakshan, 2011; Posner & Rothbart, 2007). We offer the hypothesis that IM-based SMT training may increase the efficiency of attentional and inhibitory control of information being processed in working memory, which may occur through a number of possible mechanisms, either alone or in combination, and result in an increase in the automatization and efficient performance of working memory. This suggests that IM-based SMT training may not improve working memory by increasing capacity, but that SMT training may result in more efficient use of an individual's working memory system. As previously reviewed in this article, working memory abilities are associated with increased performance proficiency in a wide range of complex cognitive performance situations (fluid reasoning, general intelligence, language acquisition, long-term memory storage, reading, and mathematics).

Another emerging explanation for interval timing improvement suggests that elementary timing tasks may represent a form of temporal *g* (Rammsayer & Brandler, 2007). Rammsayer and Brandler (2007) recently reported that measures of temporal *g*, which are very similar to the underlying temporal processing required by IM, are more strongly correlated ($r = .56$) with psychometric g than the standard *reaction time g* ($r = -.34$), the traditional approach to measuring the *essence* of general intelligence (Jensen, 1998). This suggests that temporal-based interval timing may be a key component of intellectual functioning.

The above working set of hypotheses is consistent with McGrew's (2013) three-level hypothesized model for explaining the efficacy if IM training. As summarized by McGrew (2013), IM training (1) increases temporal resolution (faster brain clock rate of neural oscillations), which improves neural efficiency (temporal *g*), which, in turn, (2) improves brain network communicated via increased speed and efficiency of white matter tract processing, particularly between the parietal and front regions of the brain, which, in turn, (3) results in an improved attentional control system, a key component of efficient working memory.

It is recommended that future research should investigate SMT effects at the neurological level (e.g., functional magnetic resonance imaging [fMRI] studies). This may help identify the location(s) of SMT training effects, which, in turn, could help identify relevant cognitive abilities vis-à-vis known brain–behavior relationships. The design of future SMT academic intervention studies should be expanded to include markers of hypothesized cognitive mechanisms (e.g., processing speed, working memory, executive functions, controlled attention) to ascertain which cognitive abilities may be modified via the SMT intervention, and, more important, which cognitive abilities may mediate the changes in academic outcomes. Longitudinal studies are particularly necessary to establish possible underlying domain-general causal mechanisms.

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NOTE

1. Another typical description of information processing models makes a distinction between: (1) memory systems—short-term and long-term memory, (2) types of knowledge—declarative and procedural, and (3) types of processing—controlled and automatic (Lohman, 2000).

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