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The Science Behind Interactive Metronome:

An Integration of Brain Clock, Temporal Processing, Brain Network and Neurocognitive Research and Theory

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Author information and conflict of interest disclosure

Dr. Kevin S. McGrew, Ph.D., is an Educational Psychologist with expertise and interests in applied psychometrics, intelligence theories and testing, human cognition, cognitive and non-cognitive individual difference variables impacting school learning, models of personal competence, conceptualization and measurement of adaptive behavior, measurement issues surrounding the assessment of individuals with disabilities, brain rhythm and mental timing research, and improving the use and understanding of psychological measurement and statistical information by professionals and the public. Prior to establishing IAP, Dr. McGrew was a practicing school psychologist for 12 years. McGrew received his Ph.D. in Educational Psychology (Special Education) from the University of Minnesota (1989).

Dr. McGrew is currently Director of the *Institute for Applied Psychometrics* (IAP), a privately owned applied research organization established by McGrew. He is also the *Research Director for the Woodcock-Muñoz Foundation* (WMF), Associate Director for *Measurement Learning Consultants* (MLC), and a *Visiting Professor in Educational Psychology* (School Psychology) at the University of Minnesota.

Dr. McGrew authored the current manuscript in his role as the Director of IAP. The majority of this working paper comes from the first draft of a work-for-hire manuscript financed by Interactive Metronome®. The opinions and statements included in this report do not reflect or represent the opinions of WMF, MLC, or the University of Minnesota. More complete professional information, including his professional resume and conflict of interest statement, can be found at the MindHub™.

[1] The current working paper is a summary and expansion of Dr. Kevin McGrew's 2012 Interactive Metronome Professional Conference Keynote Presentation (*I think…therefore IM*) were the complete explanatory model was presented. This presentation is available for viewing at YouTube by clicking here. Dr. McGrew also maintains a blog (The Brain Clock Blog) devoted to brain clock and neurotechnology interventions and research.

The Science of Interactive Metronome: Executive Summary

Cognitive *focus* plays a crucial role in success or failure in school, work, and almost all aspects human performance. Yet, few of us receive formal training on how to improve our focus (control our attention). Contemporary brain research, which is described in this working paper, and which is briefly summarized below, has shed light on the nature of cognitive focus and has provided technology to train and maintain a "focused brain."

The human mind has a limited capacity to engage in laser-beam like focus or *controlled attention*—up to 20 to 30 minute at maximum. Contemporary brain research describes focus or controlled attention as the ability to direct one's attentional spotlight on only task relevant information in one's mental workspace (*working memory*). This requires constant monitoring and timely feedback to the attentional control center regarding the status of one's "locked on" focus status. When focused, cognitive control mechanisms are constantly monitoring performance and immediately detect and deflect outside distractions and self-generated *mind wandering*. Focus training can result in the "quieting of the busy mind."

McGrew (2012) has presented a *three-level explanatory model of the IM effect* which is presented in Figure 1. Briefly, IM technology is believed to improve the resolution and efficiency of an individual's *internal brain clock(s)* and *temporal processing*. In turn, this increased *neural efficiency*, which is hypothesized to result in more efficient brain connectivity, communication, and synchronization via increased integrity of the brains *white matter tract* communication system, produces more efficient communication between critical *brain networks*. In particular, research and theory suggests that IM technology increases the efficacy of the *parietal-frontal brain network*, the brain network most associated with general intellectual functioning, working memory, controlled attention and executive functions.

IM technology incrementally teaches individuals to focus exclusively on a target tone and deploy cognitive tools to deflect distractions, most likely through improvements in the efficiency of communication within the parietal-frontal brain regions. It is hypothesized that IM technology can train individuals to enhance their ability to invoke *on-demand-focus* or *controlled attention*. The IM real-time millisecond feedback requires the user to develop the ability to block out external distractions and mind wandering—and thus, stay focused. Over time, and with sustained motivated practice, it is possible to train the brain to engage in increased on-demand focus. Although the most observable outcome of IM training may be better focus or controlled attention (and thus working memory and cognitive performance), it is suggested that this outcome is likely due to IM producing underlying changes to complex and critical brain and neurocognitive mechanisms. *McGrew's (2012) three-level explanatory IM model* is currently the best reason-, logic-, and theoretical-based set of hypotheses to explain the *IM effect*.

The primary conclusions from the detailed scientific explanation of the *IM* are:

- The diversity of domains positively impacted by IM technology is due to IM improving the function of crucial brain-based *domain-general* neurocognitive mechanisms.
- The precise, real-time IM millisecond feedback impacts the *temporal processing resolution* of the *internal brain clock*, which in turn improves *neural efficiency*—and thus, more efficient temporal and information processing in the brain.
- The *IM effect* appears to be the result of increased efficiency and synchronization of communication between the primary brain structures that comprise the *functional brain networks* involved in performing both the cognitive and motor demands of IM training.
- IM technology may be improving brain network communication, especially within the major brain networks at the core of the *P-FIT* (parietal-fontal integration) model of general intelligence. IM technology may be improving the efficiency of the parietal-frontal brain network which is critical to general intellectual functioning, working memory, controlled attention, and overall cognitive efficiency.
- One of the most important IM training outcomes (but not the only outcome) is improved focus via increased efficiency of the *attentional control system* (ACS) that maintains goal related information active in working memory in the presence of internal (mind wandering) and external distractions. Improvement in efficiency of executive functions and working memory results in more efficient complex cognitive processing and learning.

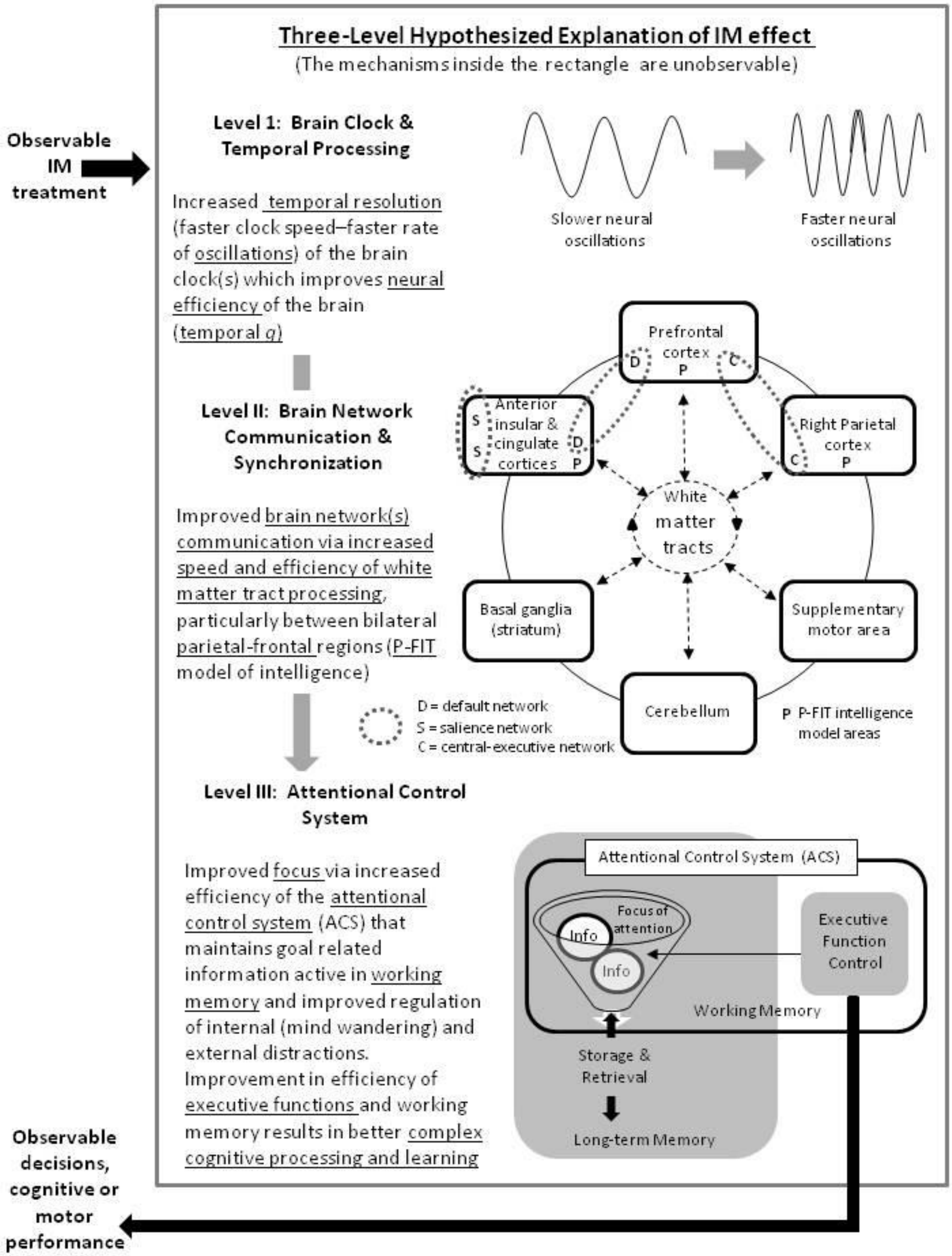


Figure 1: Three-Level Hypothesized Explanation of the *IM effect* (McGrew, 2012)

This working paper is an integration of research and theory that attempts to explain the science behind the positive outcomes of the *Interactive Metronome* rehabilitative and brain training neurotechnology (the *IM effect*). A three-level explanatory model involving three different levels of brain and neurocognitive constructs (McGrew, 2012) is described.[2] The three-levels are presented in the visual summary in Figure 1. Although the current text focuses on explaining the *IM effect* on cognitive functions (focus, controlled attention, working memory, executive functions), the three-level hypothesized model should be considered a *general explanatory framework* for understanding the positive *IM effect* in other human performance domains as well (e.g., recovery from stroke; gait; motor coordination).

The three-level model described here can also be viewed as an IM-free integration of research and theory that explains the relations between the temporal processing (temporal *g*) of the human brain clock (s), brain regions and networks, brain network communication and synchronization (the parietal-frontal integration theory of intelligence [P-FIT] in particular), and the neurocognitive constructs of controlled attention (focus), working memory, and executive functioning.

Interactive Metronome: Brief Description and Summary of Research

Interactive Metronome® (IM) is a rehabilitative and brain training neurotechnology that combines the concept of a musical metronome with a computer-based program that accurately measures and facilitates the improvement of an individual's rhythm and timing. IM training involves reducing the mean negative synchronization error during normal tracking of a regularly occurring auditory tone metronome beat. Participants receive feedback through a guidance system as they progress through interactive exercises. Although feedback is provided through both visual and auditory 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 ("on target zone"), or past* the regularly occurring auditory metronome beat. The accuracy of participants' expectancy response to the metronome beat is provided in milliseconds, 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.

The purpose of IM training is to improve participants' synchronized metronome timing and rhythmicity by reducing the latency between the onset of the metronome beat and participants' expectancy response to the beat. After approximately three to four weeks of training, or 15-18 one-hour sessions, participants are typically able to respond to within approximately 15 milliseconds on either side of the beat. This compares to the average 80-100

[2] The current working paper is a summary and expansion of Dr. Kevin McGrew's 2012 Interactive Metronome Professional Conference Keynote Presentation (*I think…therefore IM*) were the complete explanatory model was presented. This presentation is available for viewing at YouTube by clicking here.

millisecond latency response prior to training. At the completion of training, participants typically have engaged in approximately 25,000 synchronized metronome repetitions. These synchronized movements are the physical indication of one's expectancy of the onset of the metronome beat. The various movements incorporated in training include clapping hand-to-hand with a sensor on one palm, taping the palm sensor lightly on the thigh, and taping floor sensors with either the toe or back of the foot.

IM research has reported positive *IM effects* for ADHD behavior, speech and language disorders, sports performance (golf and tennis), improvement of gait, reading achievement, and traumatic brain injury rehabilitation (Beckelhimer, Dalton, Richter & Harmann, 2011; Libkuman & Otani, 2002; McGrew & Vega, 2009; Nelson, 2012; Ritter, Colson & Park, 2013; Shaffer, Jacokes, Cassily, Greenspan, Tuchman & Stemmer, 2001; Sommer and Rönnqvist, 2009; Taub, McGrew & Keith, 2007). The diversity of domains positively impacted by IM technology begs the question—"how can a single neurotechnology produce positive outcomes across such a diverse range of human performance domains?" The only plausible scientific answer is that IM must be impacting a domain-general ("jack-of-all-trades") brain-based mechanism or set of mechanisms.

IM as a domain-general brain mechanism neurotechnology

Domain-specific versus domain-general brain and learning mechanisms

Most all children and adults have learned to ride a bike for recreational purposes. We have over learned the act of cycling so we can bike with little in the way of deliberate thinking. We do not need to consciously tell each leg to move in a certain pattern, monitor how accurately our legs moved, tell our arms to turn the handle bars, etc. The resources of our immediate memory are free to observe others walking nearby, look at the interesting decorations of a house, talk to our riding partner, think about work, etc.

If a person practiced recreational biking one hour a day for four weeks straight the person may improve their recreational biking behavior. However, one would not expect this recreational cycling practice to transfer to improvement in speaking, reading comprehension, work performance, or golf. This is an example of a circumscribed or compartmentalized set of skills or behaviors that have been over-learned (i.e., automatized) and that are under the control of a set of narrow domain-specific (i.e., recreational biking) brain mechanisms. *Domain-specific* mechanisms are specialized brain mechanisms that processes only specific kinds of information dedicated to learning about a particular area of knowledge (Rakison & Yermolayeva, 2011). Domain-specific mechanisms are important for automatic efficient human performance in many day-to-day environments but, in general, improvement via training is typically restricted to improvement within the specific limited set of skills and behaviors.

In contrast, a domain-general mechanism is one that if changed results in changes in performance across multiple and diverse areas of human functioning. According to Rakison and Yermolayeva (2011), *domain-general* mechanisms are "processes that are both knowledge universal and modality universal in that the same mechanisms function across a wide range of knowledge areas and inputs" (p.135). Such an underlying brain-based mechanism is a "jack-of-all-trades" that can be applied to a wide range of novel problems and performance (Chiappe & McDonald, 2005). **The only viable explanation for the diversity of the *IM effect* is the hypothesis that IM is impacting a fundamental domain-general brain-based cognitive mechanism, network, or set of mechanisms and networks**.

Another source of research supporting the concept of a domain-general brain mechanism is the finding that a variety of clinical disorders have been associated with poor brain clock timing and temporal processing. These include ADHD, dyslexia, age-related deficits and declines (e.g., Alzheimer's), motor coordination and production disorders (e.g., apraxia, cerebral palsy, gait disorders), Parkinson's disease, schizophrenia, speech and language disorders (e.g., dysfluency, aphasia, apraxia), traumatic brain injury (TBI), and autism (McGrew & Vega, 2009).

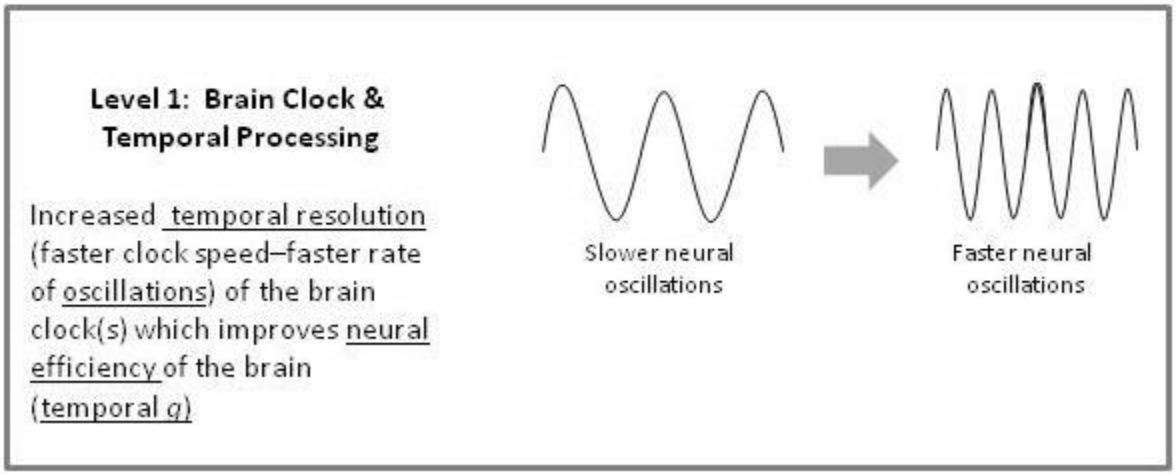
The convergence of research by mental timing scholars studying normal cognitive processes and research implicating the efficiency of temporal processing in a variety of clinical disorders is consistent with the notion of a domain-general master internal brain clock (or systems of clocks).

But what is this domain-general mechanism or set of mechanisms that produces the variety of diverse *IM effects*?

A three-level theoretical and research-based explanation of the *IM effect*

Research and theory suggests that understanding the science behind the *IM effect* requires three interrelated levels of explanation involving different levels of brain and neurocognitive constructs (McGrew, 2012). The three-levels are presented in the visual summary in Figure 1. Although the current text focuses on explaining the *IM effect* on cognitive functions (focus, controlled attention, working memory, executive functions), the three-level hypothesized model should be considered a *general explanatory framework* for understanding the positive *IM effect* in other human performance domains as well (e.g., recovery from stroke; gait; motor coordination). **The three-level model described here can also be viewed as an IM-free integration of research and theory that explains the relations between the temporal processing (temporal *g*) of the human brain clock (s), brain regions and networks, brain network communication and synchronization (the parietal-frontal integration theory of intelligence [P-FIT] in particular), and the neurocognitive constructs of controlled attention (focus), working memory, and executive functioning.**

Level 1: The Brain Clock and Temporal Processing



The human brain measures time continuously. This capability is important as it subsumes a variety of human performance mechanisms (e.g., rhythm perception and production; synchronized motor behavior) critical to many human behaviors (Lewis, 2002; Nobre & O'Reilly, 2004). Timing is essential to human behavior and it is hard to find any complex behavioral process where mental timing is not involved (Lewis & Walsh, 2005; Mauk & Buonomano, 2004). Neurodevelopmental research highlights the importance of mental timing as a key brain mechanism for learning and adaptation as a primitive "time sense" has been identified as early as infancy and which eventually increases in precision due to maturation of the central nervous system (Droit-Volet, 2013).

Temporal processing is generally defined as the processing of time-related information. To deal with time, organisms (animal and human) have developed multiple timing systems that span more than 10 orders of magnitude with various degrees of precision. According to Buhusi and Meck (2005), humans have developed three general classes of timing systems (*circadian*, *interval*, and *millisecond* timing). IM operates as per the *millisecond timing system* which is involved in a number of classes of human behavior (e.g., speech, music, attention, motor control). This precise timing system (separated from the motor coordination functions) primarily involves the brain structures of the cerebellum, basal ganglia, and the right parietal and dorsolateral prefrontal cortices (Buhusi & Meck, 2005; Buonomano & Karmarkar, 2002, Lewis & Miall, 2006).

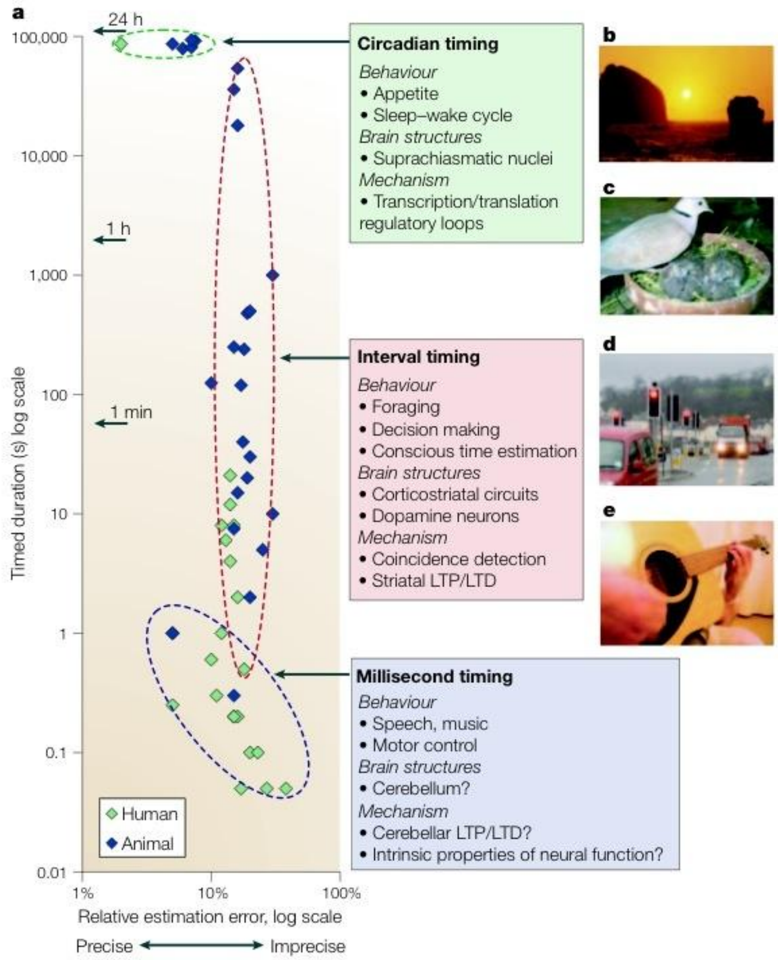


Figure 1 | **Timing across different timescales. a** | A compilation, which is by no means exhaustive, of data from various studies[29,130–141] that indicate the precision of humans and other animals in various timing tasks. Performance is precise (but less flexible) in a narrow range around 24 h (circadian timing), less precise (but more flexible) in a wide seconds-to-minutes-to-hours range (interval timing), and is of mixed precision in the sub-second range (millisecond timing) in which performance is probably linked to the intrinsic properties of the neural system involved[29]. **b**–**e** | Circadian rhythms[13] are most recognizable in nature (**b**), but interval and millisecond timing also guide fundamental animal behaviours. For example, although female ring doves use circadian-timing strategies to coordinate egg incubation, males use interval-timing strategies[31] (**c**). Interval timing is involved in decision making[2,3] (**d**), and millisecond timing is central to the playing of music[30] (**e**). LTD, long-term depression; LTP, long-term potentiation.

The dominant theoretical explanation of millisecond-based human behavior is the hypothesis that humans possess a centralized internal brain clock that functions as per the *pacemaker–accumulator model* (PAM; Buhusi & Meck, 2005; Karmarkar & Buonomano, 2007).[3]

[3] 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). In addition, the striatal beat frequency model (SBF) is now seen as a potentially more plausible biological model of the internal clock (Droit-Volet, 2013). 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

The hypothesized internal PAM brain clock consists of a *pacemaker* that continuously generates neural ticks or pulses. These neural ticks are transferred and collected in the *accumulator*. The neural counts are then transferred to a *working memory* system or buffer. The contents of the short-term working memory are then compared against a reference standard in the long-term memory (*reference memory*). Finally, the *decision* level of the PAM uses a *comparator* that determines an appropriate response based on decision rules which involve 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 what is accumulated in working memory (viz., are they "close?")" (Taub et al., 2007, p. 858-859).

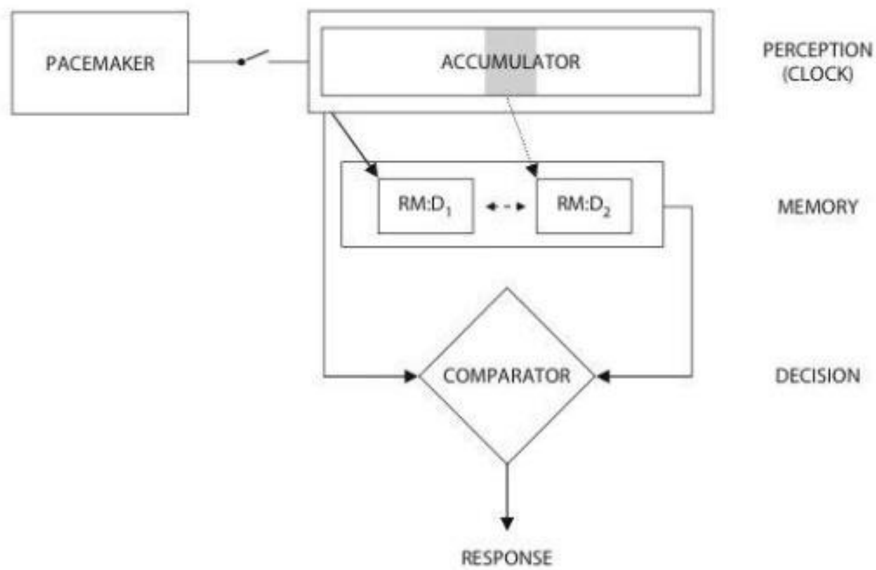


Figure 4. Schematic of the information-processing version of the scalar expectancy theory adapted to a simultaneous timing condition. At the perceptual level, or clock level, there is a pacemaker–accumulator (or counter) device, with a switch component between the two. The diagonal arrows indicate that, once a level of accumulation is reached, it is with another internal representation in reference memory (RM) that the interval for a given trial will be compared. The accumulation level that has to be reached may vary from trial to trial (gray zones in the accumulator). The bidirectional arrow between RM components indicates that the internal representations may exert mutual influence. D_1, D_2, Distribution 1 or 2, associated with a given level of accumulation of pulses. From "Overloading Temporal Memory," by S. Grondin, 2005, *Journal of Experimental Psychology: Human Perception and Performance, 31*, p. 876. Copyright 2005 by the American Psychological Association. Reprinted with permission.

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functions located in a number of brain structures (often in network pathways, circuits 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; Lewis & Miall, 2006; Nobre & O'Reilly, 2004; Taub, McGrew & Keith, 2007). For the current IM discussion, resolving which theoretical model is most plausible is not important. The important point is that the human brain posses some basic neurocognitive mechanism (or distributed mechanisms) that functions as an internal brain clock.

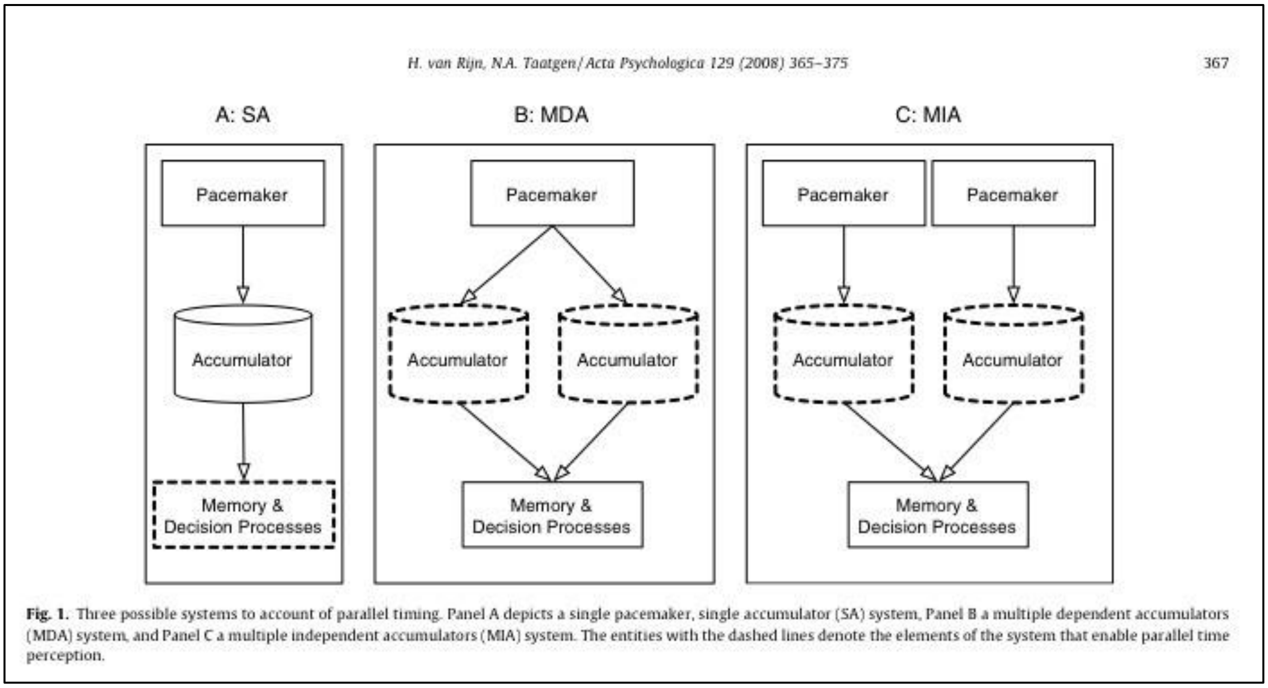
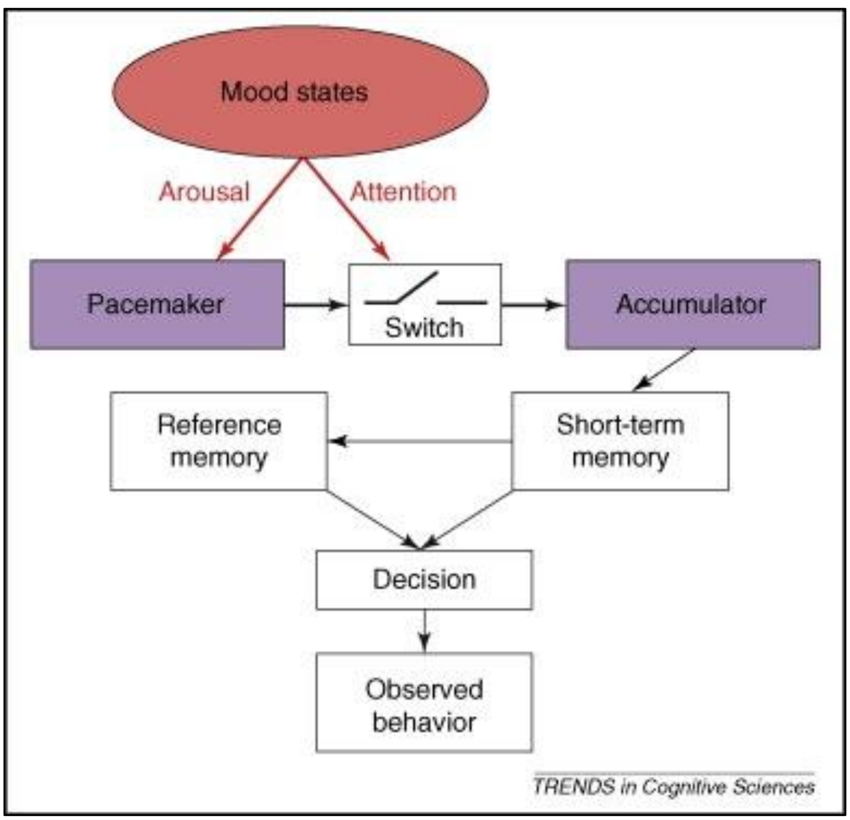


Fig. 1. Three possible systems to account of parallel timing. Panel A depicts a single pacemaker, single accumulator (SA) system, Panel B a multiple dependent accumulators (MDA) system, and Panel C a multiple independent accumulators (MIA) system. The entities with the dashed lines denote the elements of the system that enable parallel time perception.



In the case of IM performance, if the working-to-reference memory comparison reflects "on target" synchronization, the participant receives millisecond-based IM auditory feedback that they are on target" and the PAM-based decision is to continue the synchronized tapping pace without adjustment. However, if the comparison suggests that synchronization is "out of phase" (as indicated by the IM audio feedback) the decision-making comparator component of the PAM brain clock detects the discrepancy and corrective actions are initiated to return to good synchronization. **When conceptualized from the model of a human brain clock, it is hypothesized that IM participants processes the synchronized timing demands thru the components of the human brain clock which, over time, increases the efficiency of the person's internal brain timing.**

Neural efficiency

As noted in Level I of Figure 1, it is hypothesized that IM increases the *temporal resolution* or *clock speed* of the above described PAM master internal brain clock.[4] A higher mental clock rate enables individuals to perform sequences of mental operations faster. A higher mental clock rate also reduces the chances that task irrelevant information will interfere with mental processing. The *neural efficiency* hypothesis (Jensen, 1982, 1998, 2006) suggests that the faster the brain's synapses fire the more efficient and faster the transmission of information within the brain, both at the level of individual nerve synapses and eventually at the level of fine-tuned communication across brain networks. Neural efficiency explains how quickly, after a neuron has fired, it can recharge itself and fire again. Faster recharge rates allow for more frequent firing of nerve synapses during cognitive or motor tasks.

The neural efficiency hypothesis has been the dominant explanation of individual differences in general intelligence (Haldemann, Stauffer, Troche & Rammsayer, 2012). The primary focus of the neural efficiency model of intelligence is that differences in rates of *neural oscillations* exist between individuals (Haldemann et al., 2012; Jensen, 1982, 1998, 2006). Neural oscillations are represented by the two different oscillation wave forms to the right in Level I in Figure 1. The first oscillation wave form reaches its peak neural firing stage three times, while the adjacent wave form demonstrates five different neural peak firings. The valleys represent the neural refractory (recovery) periods. In the slower model, where the firing peaks and recovery valleys are spaced farther apart, recovery takes more time. In the faster five-peaked wave pattern, the refractory or recovery times (valleys) are briefer and closer together in time. The neural efficiency hypothesis suggests that individual differences in speed of cognitive information processing and intelligence can be explained by differences in neural oscillation rates. The higher the oscillation rate the shorter are the refractory phases, leading to faster transmission of neural encoded information in the brain.

[4] Or, as noted previously, IM may be impacting the temporal resolution or clock speed of multiple distributed brain clocks.

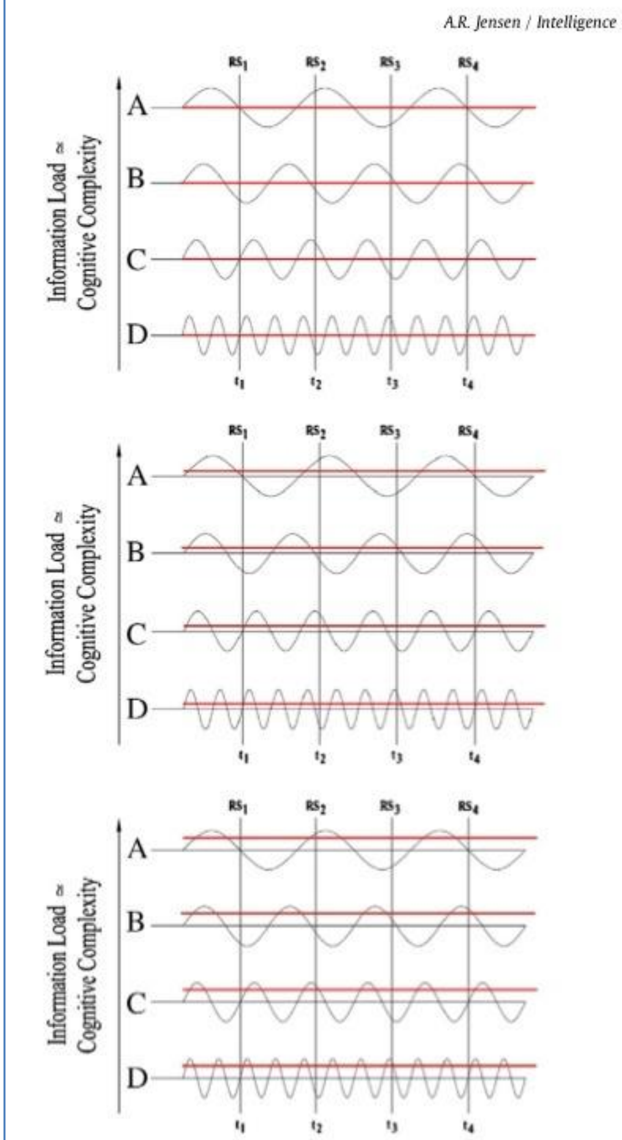


Fig. 1. In the typical RT experiment, the Reaction Stimulus (RS) is presented either randomly or at equal intervals as shown in Fig. 1. The Person's (P's) Reaction Time (RT) is recorded on every trial. The wave of neural excitatory potential for reaction oscillates. It is non-reactive when the oscillating wave of reaction potential is below the person's excitatory threshold (as shown here by the horizontal lines); reactive when above. Therefore, in any random series of RT tests, Persons A, B, C, and D will differ predictably in their respective mean RT in accord with their differing respective rates of neural oscillation. Note in the successive three panels of Fig. 1 that as the Information Load (Cognitive Complexity) of the task increases, the person with the faster Oscillation Rate (OsR) will be at peak power more often per unit of real time.

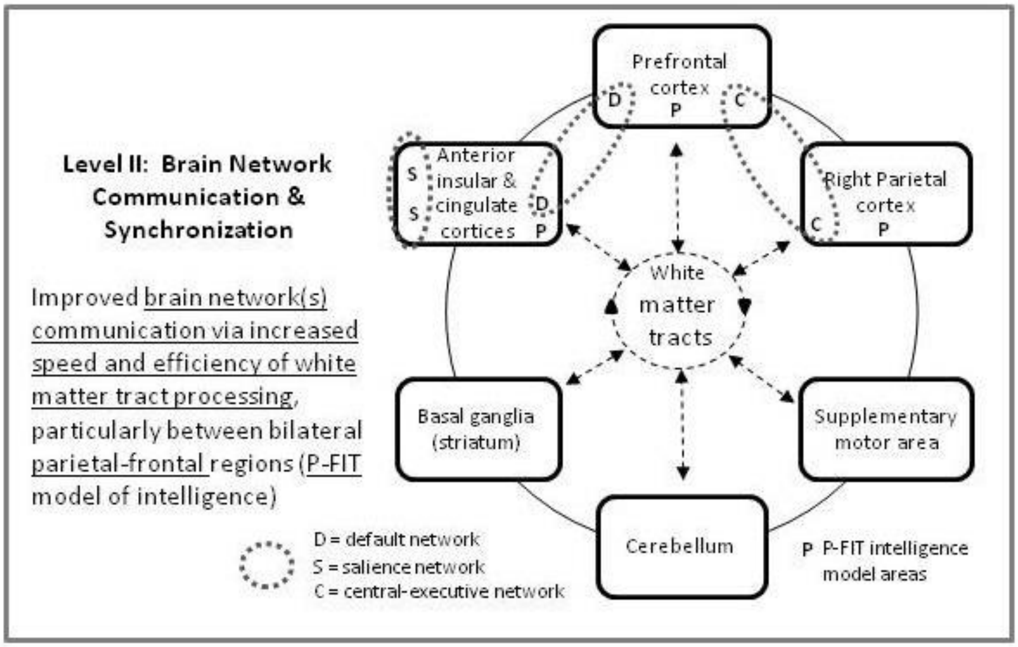
In conclusion, neurons which repeatedly fire, recharge, and fire more quickly during a cognitive, sensory or motor task produce better cognitive, sensory or motor performance. **It is hypothesized that IM impacts the temporal processing resolution of the internal brain clock, which in turn improves neural efficiency—and thus, more efficient temporal processing in the brain.**

Temporal Resolution Power Hypothesis

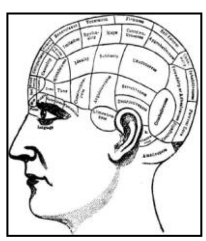
The key hypothesized *IM effect* at Level I is an increase in neural efficiency via increased *temporal resolution* of the brain clock. The *temporal resolution power (TRP) hypothesis* (Rammsayer & Brandler, 2002, 2007) "refers to a hypothetical oscillatory process in the brain to account for the relationship between efficiency and speed of information processing as well as psychometric intelligence. According to this view, higher neural temporal resolution leads to faster information processing and to better coordination of mental operations resulting in better performance on intelligence tests" (Haldemann, Stauffer, Troche, & Rammsayer, 2012; p. 182). Support for the link between increased cognitive efficiency vis-à-vis increased temporal resolution of the human brain clock has been demonstrated in a systematic series of mental timing studies over the past decade (Brandler & Rammsayer, 2003; Haldemann et al., 2012; Helmbold, Troche & Rammsayer, 2006, 2007; Rammsayer, 2001, 2002, 2010; Rammsayer & Altenmuller, 2006; Rammsayer & Brandler, 2002, 2007; Rammsayer, Hennig, Haag & Lange, 2001; Rammsayer & Troche, 2010a, 2010b; Rammsayer & Ulrich, 2001; Ulrich, Nitschke & Rammsayer, 2006; Volz, Nenadic, Gaser, Rammsayer, Häger & Sauer, 2001) .

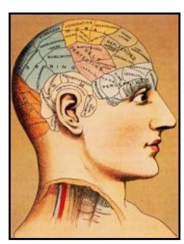
In summary, as illustrated at Level I in Figure 1, a review of basic brain clock, temporal processing resolution, and IM efficacy research suggests that **the most viable scientific explanation of the *IM effect* is that the precise IM millisecond feedback is most likely fine-tuning the temporal resolution of the internal brain clock, a crucial domain-general mechanism that produces increased neural efficiency which, in turn, improves the efficiency of cognitive, sensory and motor behaviors via more efficient synchronization of communication between brain regions and networks.**

Level II: Brain Network Communication and Synchronization



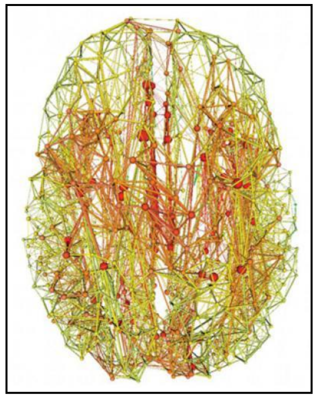
Man has always known that the brain is the center of human behavior. Early attempts at understanding which locations in the brain controlled different functions were non-scientific and included such practices as *phrenology*. This pseudoscience believed that by feeling the bumps of a person's head it was possible to draw conclusions about specific brain functions and traits of the person. Eventually brain science revealed that different regions of the brain where specialized for different specific cognitive processes. This has been called the *modular* or *functional* specialization view of the brain, which is grounded in the conclusion that different brain areas acted more-or-less as independent mechanisms for completing specific cognitive, sensory and motor functions (Bressler & Menon, 2010).





Brain Networks

Contemporary neuroscience now recognizes that the human brain processes information via different brain circuits or loops, which at a higher level are studied as large-scale *brain networks*. Although the modular view still provides important brain insights, the research evidence suggests that it has serious limitations and might in fact be misleading (Bressler and Menon, 2010). The emerging brain network research is large and has addressed various brain and neurocognitive functions (see Bressler & Menon, 2010; Brewer, Worunsky, Gray, Tang, Weber & Kober, 2011; Colom, Haier, Head, Álvarez-Linera, Quiroga, Shih & Jung, 2009; Cole, Yarkoni, Repovs, Anticevic & Braver, 2012; Deary, Penke & Johnson, 2010; Haier, 2009; Jung & Haier, 2007; Lutz, Slagter, Dunne & Davidson, 2008; McVay & Kane, 2012; Toga, Clark, Thompson, Shattuck & Van Horn, 2012; van den Heuvel & Sporns, 2011).



Large-scale brain network research suggests that cognitive, sensory and motor functioning is the result of communication between different brain systems distributed throughout the brain. Different areas of the brain, often far apart from each other within the geographic space of the brain, are communicating through a fast-paced synchronized set of brain signals. These networks can be considered preferred pathways for sending signals back and forth to perform a specific set of cognitive, sensory, or motor behaviors. As described at Level I (see Figure 1), it is hypothesized that IM improves the flow and synchronization within the brain via increased temporal resolution of the internal brain clock.

The work of Bressler and Menon (2010) serves as the model for placing the *IM effect* in the context of contemporary brain network research. According to Bressler and Menon (2010), "a large-scale functional network can therefore be defined as a collection of interconnected brain areas that interact to perform circumscribed functions." More importantly, component brain areas in these large-scale brain networks perform different roles. Some act as controllers or task switchers that coordinate, direct and synchronize the involvement of other brain networks. Other brain networks handle the flow of sensory or motor information and engage in conscious manipulation of the information in the form of "thinking."

Neuroscientists have identified a number of core brain network nodes or circuits. Referencing the ground breaking network work of Mesulam (1990), Bressler and Menon (2010) describe at least five major core functional brain networks—*spatial attention, language, explicit memory, face-object recognition, and working memory-executive function*. Bressler and Menon's (2010) research review suggested two additional important functional networks—the default mode and salience networks. Three of the aforementioned core networks appear to be particularly relevant for cognitive performance on IM, and in turn, are most likely fine-tuned as a result of IM treatments.

Three major functional brain networks most likely involved in the IM effect

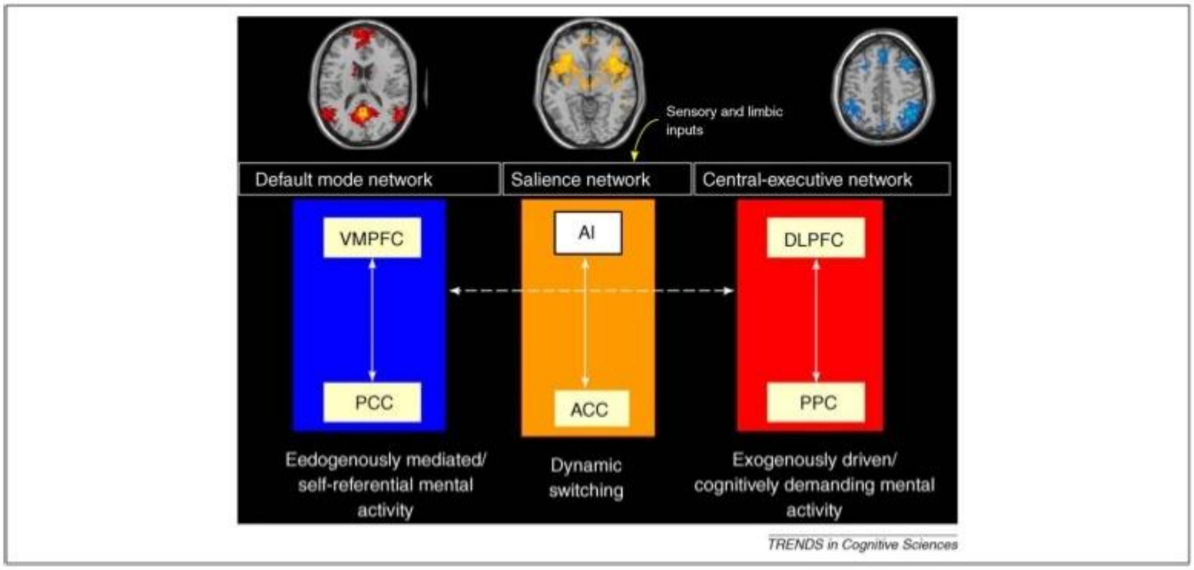


Figure 7. Multi-network switching initiated by the salience network. It is hypothesized that the salience network initiates dynamic switching between the central-executive and default-mode networks, and mediates between attention to endogenous and exogenous events. In this model, sensory and limbic inputs are processed by the AI, which detects salient events and initiates appropriate control signals to regulate behavior via the ACC and homeostatic state via the mid and posterior insular cortex. Key nodes of the salience network include the AI and ACC; the default-mode network includes the VMPFC and PCC; the central-executive network includes the DLPFC and PPC. (Based on [129] and [130].)

The default mode (DMN) or *default network* is what a person's brain does when not engaged in specific tasks. It primarily involves the ventral medial prefrontal cortex (VMPFC) and posterior cingulate cortex (PCC) of the brain (Bressler & Menon, 2010). It is the busy or active part of a person's brain when a person is mentally passive. According to Bressler and Menon (2010) the "DMN is seen to collectively comprise an integrated system for autobiographical, self-monitoring and social cognitive functions" (p. 285). It has also been characterized as responsible for *REST* (rapid episodic spontaneous thinking), *TUT's* (task unrelated thoughts), or what generically is referred to as *mind wandering* (Bressler & Menon, 2010; Kane & McVay, 2012; McVay & Kane, 2012; Risko, Anderson, Sarwal, Engelhard & Kingstone, 2012; Schooler, Smallwood, Christoff, Handy, Reichle & Seyette, 2011; Smallwood, 2010; Unsworth, McMillen, Brewer & Spillers, 2012). Individuals typically engage in spontaneous mind wandering when not working on a specific task or when completing a task that is so automatized (e.g., recreational riding of a bike) that a person's mind is free to wander and generate spontaneous thoughts.

The *salience network* is a control or network switcher associated with the brain structures of the anterior insula (AI) and anterior cingulate cortex (ACC). The salience network monitors information from within (internal input—i.e., mind wandering) and from a person's external world. The salience network can be considered the brains air traffic control center. Its job is to scan incoming internal and external information and decide which information is most urgent, task relevant, and which should receive priority in the queue of sending brain signals to different areas of the brain for processing. This controlling network must suppress either the default or central-executive networks (defined next) depending on the task at hand. This decision-making and distribution and synchronization of information is most likely facilitated by efficient neural timing as regulated by the master internal brain clock(s).

Finally, the *central-executive network* (CEN) engages in higher-order cognitive processing and attentional control (Bressler & Menon, 2010). The central-executive network is primarily associated with the dorsolateral prefrontal cortex (DLPFC) and right posterior parietal cortex (PPC). The CEN is active when individuals engage their conscious brain to work on a problem, place information in working memory as they think (e.g., attempting to comprehend the meaning of a sentence just read from a book), or focus their attention on a task or problem. The CEN is primarily engaged when people are "thinking" and must focus their controlled attention.

According to Bressler and Menon, not only is this large scale brain network research providing a better understanding of normal cognitive, sensory and motor behavior, it is providing insights regarding clinical disorders of the brain. Poor synchronization between the three major brain networks has been implicated in Alzheimer's, ADHD, schizophrenia, autism, the manic phase of bipolar and Parkinson's (Bush, 2010; Bressler and Melon, 2010; Castellanos & Proal, 2012), disorders that have all been linked (at Level I in Figure 1) to neural brain clock timing. If the synchronized millisecond based communication between and within these large networks is compromised, and, if the network traffic controller (the salience network) is disrupted in particular, efficient and normal cognitive, sensory, or motor behavior will most likely be compromised.

IM and the three brain networks

Task analysis of IM, and a comparison to the task demands of other researched attentional control tasks, suggests that the *IM effect* may be due to increased efficient communication between the default, salience, and central-executive brain networks. The ability to stay in the "right on zone" requires IM participants to constantly control on-line real time attention and focus. This requires the ability to shut down the mind wandering of the default network and to inhibit responding to external distracting stimuli from the immediate environment. Any momentary lapse of attentional control or focus, where attention is captured by a stray external stimulus or internal thought, typically results in a movement out of the "right on zone" which is meet with immediate corrective IM auditory feedback. Thus, the salience network must shut down activity of the default mode and not allow the central executive network to react to environmental distractions or to place task-irrelevant information in active working memory to "think about." This is an extremely hard task for many IM novices, but with sustained practice, the ability to develop sustained task-focused concentration and attention can be achieved and typically becomes progressively more effortless.

This form of attentional control is conceptually similar to that required by certain Buddhist approaches to meditation. *Mindfulness* or *focused attention* (FA) mediation (Lutz, Slagter, Dunne & Davidson, 2008; Sedlmeier, Eberth, Schwarz, Zimmermann, Haarig, Jaeger & Kunze, 2012) requires sustaining selective attention moment-by-moment to a chosen object (much like the IM target tone) and constant monitoring of the quality of attention so to stay focused and in the zone (not be distracted by mind wandering or other extractions). These procedures are believed to "train skills in sustaining the focus of attention, detecting distractions, disengaging from distractions, and redirecting the attention to the object one should focus on. These skills have been identified as basic attentional processes, and they are well connected to specific brain regions" (Sendler et al., 2012; p. 6). The primary difference between FA-based meditation methods and IM is that IM provides the "detect and deflect" feedback function while in FA-based meditation the participant must learn these detect and deflect skills without precise millisecond feedback.

Table 1. Comparison of three brain states

	Resting State	*Alert State*	*Meditation State*
Brain Networks	DMN including mPFC, ACC, PCC, and others	Right PFC, PC, and others	Stage 1, Lateral PFC, PC Stage 3, ACC, insula, striatum
EEG	Alpha dominance	Desynchronized EEG signal	Mixed bands including alpha, theta, gamma
ANS	Sympathetic dominance	Stage A, parasympathetic dominance; Stage B, sympathetic dominance	Parasympathetic dominance
Neuromodulator		Norepinepherine (NE)	Dopamine (DA)

At Level II in Figure 1, the primary brain-based structures that research has implicated in both the mental time keeping research and IM performance are portrayed. As described above, four of these brain structures (viz., prefrontal cortex, posterior parietal cortex, and the anterior insular and cingulate cortices) are implicated in the interaction of the default (cingulate cortex—PCC; ventral medial prefrontal cortex—VMPFC), salience (anterior insula—AI; cingulate cortex—ACC), and central-executive (dorsolateral prefrontal cortex—DLPFC; posterior parietal cortex—PPC) networks when engaging in and training controlled attention or focus.[5] The other brain structures (i.e., basal ganglia; cerebellum; supplementary motor cortex) have extensive research bases that identify them as critical to the timing or coordination of motor behaviors. **It is hypothesized that the *IM effect* is the result of increased efficiency and synchronization of communication between the primary brain structures that comprise the functional brain networks involved in performing both the cognitive and motor demands of IM training.**

[5] The primary brain structures involved in the default (D), salience (S) and central-executive (C) networks are designated by dashed ovals at Level II in Figure 1.

Review

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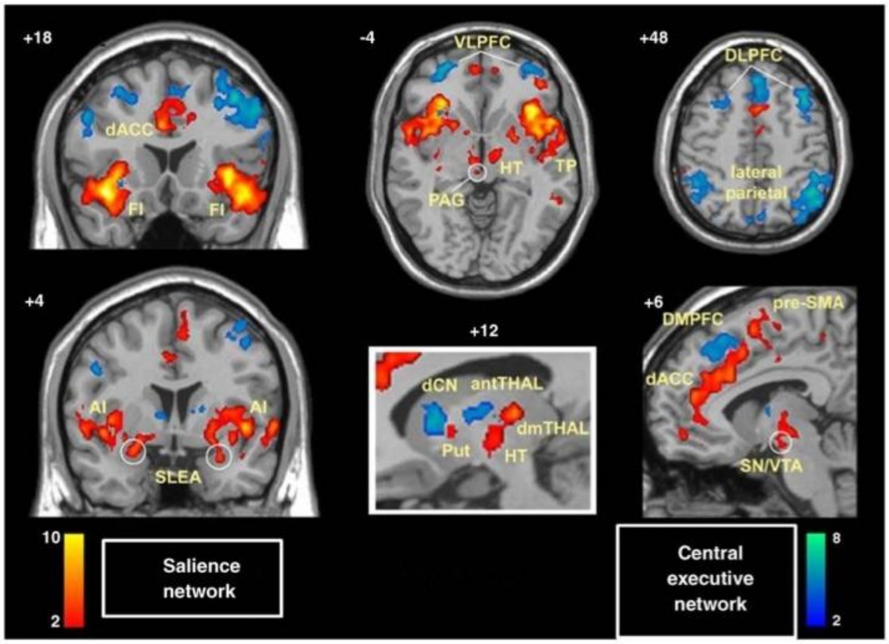
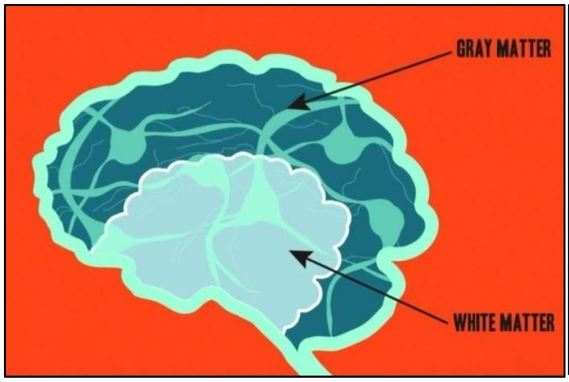


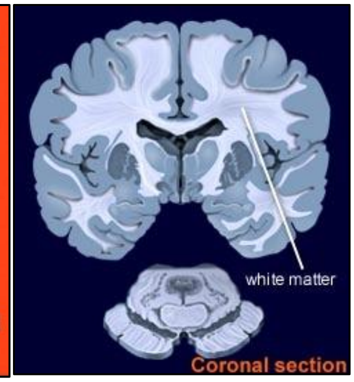
Figure 5. Two core brain networks identified using intrinsic physiological coupling in resting-state fMRI data. The salience network (shown in red) is important for monitoring the salience of external inputs and internal brain events, and the central-executive network (shown in blue) is engaged in higher-order cognitive and attentional control. The salience network is anchored in anterior insular (AI) and dorsal anterior cingulate cortices (dACC), and features extensive connectivity with subcortical and limbic structures involved in reward and motivation. The central-executive network links the dorsolateral prefrontal and posterior parietal cortices, and has subcortical coupling that is distinct from that of the salience network. (Reproduced with permission from [107].)

But what is the possible underlying communication or synchronization brain mechanism (or mechanisms) that allows for different brain networks to communicate more effectively as a result of IM training?

The P-FIT model of intelligence and white matter tracts

White matter tract integrity and maturation. *White matter tracts* are the signal transmission conduits of the brain. Different white matter tracts send signals to and from different areas of the cerebral cortex (the grey matter) and to and from the lower brain centers of the brain (see Level II in Figure 1). White matter fiber tracts can be considered the brain's information superhighway or fiber optic system that relays and coordinates communication between different brain regions and networks. The pervasive impact of white matter tract integrity is represented by Penke, Maniega, Bastin, Hernández, Murray, Royle, Starr, Wardlaw and Deary's (2012) statement that "white matter tract integrity…is a *global* property of the brain" (p.2; italics emphasis added).





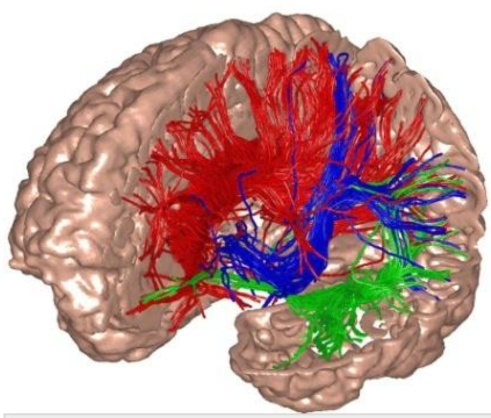


Fig. 1.

The model's global thalamocortical geometry and white matter anatomy was obtained by means of diffusion tensor imaging (DTI) of a normal human brain. In the illustration, left frontal, parietal, and a part of temporal cortex have been cut to show a small fraction of white-matter fibers, color-coded according to their destination.

All the white matter

Having recruited a group of healthy twins from 20 to 30 years old, Paul Thompson of the University of California, Los Angeles, made these pictures of their brains' white matter. This is largely composed of the fatty myelin sheaths around neurons and so reveals the brain's connections. Thompson used diffusion imaging, which measures the direction in which water diffuses through white matter, to show the speed of the connections.

This is the white matter across a whole brain. In this picture, the colours don't indicate connection speed – they merely allow the connections to be distinguished from each other. The bundle sticking out on the right are the optical tracts, leading to the eyes.

(Image: David Shattuck, Arthur Toga, Paul Thompson/UCLA Lab of Neuro Imaging)

The hypothesis is advanced that the *IM effect* may be due to increased communication efficiency between certain brain networks via increased processing speed or efficiency of the underlying white matter tracts (see Level II in Figure 1). This hypothesis, represented as Level II in Figure 1, is based on a number of related research-based findings and a recent IM-specific study with soldiers with blast related brain injuries (Nelson, 2012).

First, as previously described, the IM effect is hypothesized to be due to a positive impact on a domain-general neurocognitive mechanism. The *global* signal transmission property of white matter tracts throughout the cerebrum (Penke et al., 2012) makes white matter tracts a viable candidate as the foundation, or partial foundation, for this domain-general mechanism. This point is consistent with Droit-Volet's (2013) review of the neurodevelopmental research regarding timing and time perception in children. Droit-Volet concluded that "it is logical to try establish a link between the high variability in time estimates in young children and the development of the architecture of white matter. Indeed, a lack of maturation in white matter tissue may result in a slow rate or cortical oscillations, poorer synchronization of cortical oscillations, and/or less efficient connectivity between the different key cerebral areas (fronto-striatal system) underlying the different functions of time processing (p. 228)." Second, increased white matter tract efficiency and integrity is consistent with increase neural efficiency as described previously. Third, the hypothesized involvement of the frontal and parietal lobes during IM performance is consistent with the *parietal-frontal integration theory of intelligence* (P-FIT; Colom et al., 2009). The P-FIT model is considered by some leading intelligence scholars as the best available description of how general intelligence is distributed in the brain (Colom et al., 2009; Deary, 2012; Deary, Penke & Johnson, 2010; Hunt, 2011). The interaction and roles of the default, salience and central executive networks fit nicely with the foundational P-FIT neuroimaging and structural brain research.

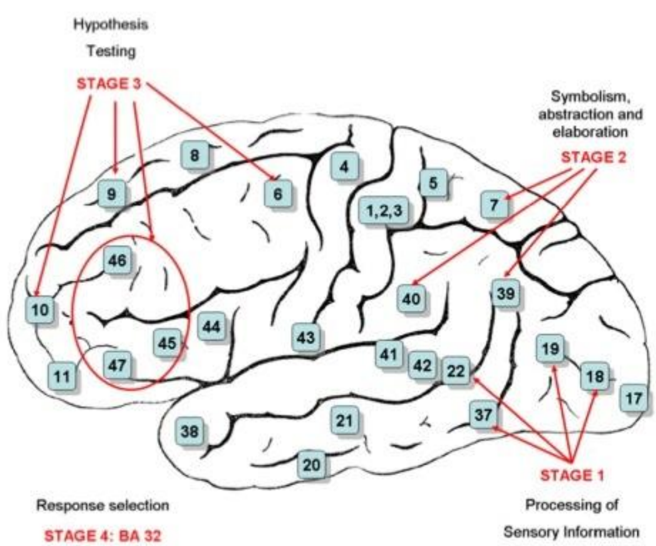


Fig. 1. Processing stages associated with specific brain regions according to the P-FIT model: processing of sensory information (stage 1), symbolism, abstraction, and elaboration (stage 2), hypothesis testing (stage 3), and response selection (stage 4). The arcuate fasciculus (i.e. the neural pathway connecting the posterior part of the temporo-parietal junction with the frontal cortex) is not shown in the figure, but also underscored by the P-FIT model.

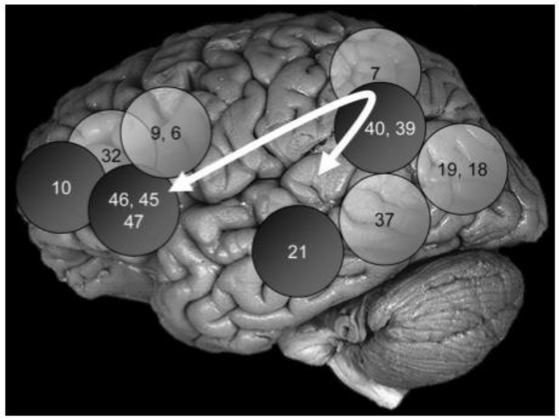


Figure 1. Brain regions by Brodmann area (BA) associated with better performance on measures of intelligence and reasoning that define the P-FIT model. Numbers = BAs; dark circles = predominant left hemisphere associations; light circles = predominant bilateral associations; white arrow = arcuate fasciculus. This figure is derived from data presented in Figure 5.

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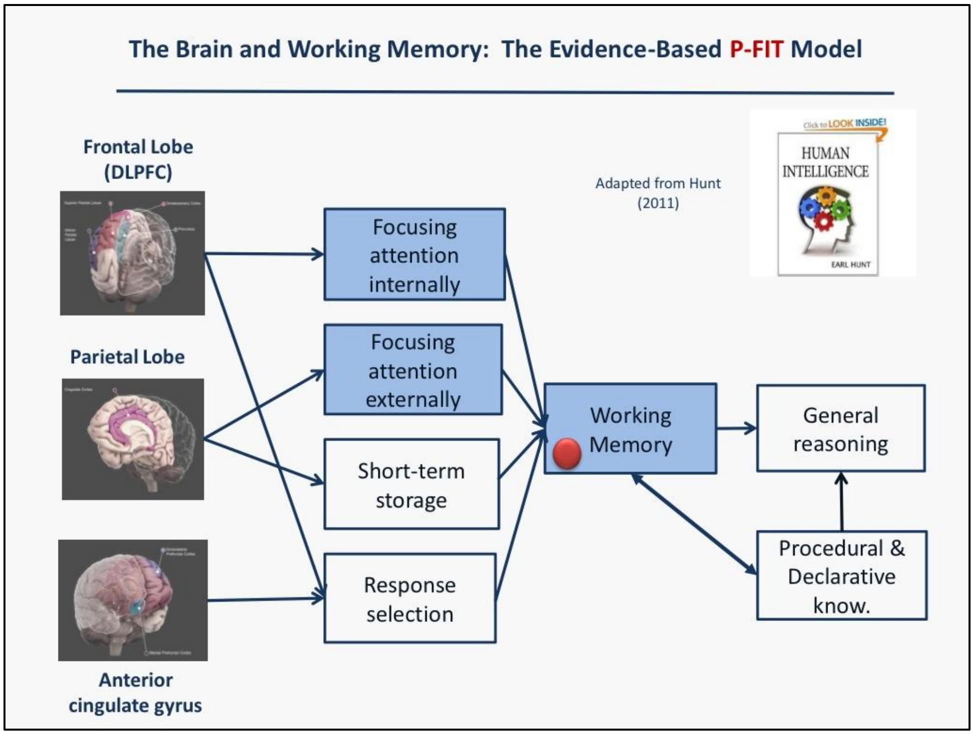
The P-FIT model and white matter integrity. The crucial role the parietal-frontal network plays in general cognitive or intellectual functioning is captured by Hunt's (2011) conclusion that the P-FIT model of intelligence is the best available description of brain-cognitive performance relations. Hunt concluded, "In summary, there is clear evidence that the working memory system, which we know is central to reasoning and general intelligence, is supported by a brain system involving regions of the frontal lobe, the parietal lobe, and the anterior cingulate cortex. I do not want to give the impression that these are the only areas involved, or that all the details of the involvement have been worked out. They have not, but the outline is clear" (p. 192). According to Hunt (2011), as per the P-FIT model of intelligence, the ability to maintain select goal-related information in focused working memory (the circles in the cone at Level III in Figure 1) are linked to both the frontal and parietal lobes. The anterior cingulate is also involved (as discussed in Level II) in response selection and directing decisions based on the information in working memory.



Recent research evidence suggests that the efficiency of the interaction between the parietal-frontal lobes (and other brain structures as per the P-FIT model) is due to increased white matter tract integrity (Deary, 2012; Deary et al, 2010; Penke, Maniega, Bastin, Hernández, Murray, Royle, Starr, Wardlaw & Deary, 2012). This research has reported "significant correlations between intelligence and parameters that reflect white matter network efficiency, indicating that not only the integrity, but also the organizational efficiency, of white mater is important for higher intelligence" (Deary et al., 2010, p. 208). Penke et al. (2012) also reported that white matter tract integrity exerts a significant effect on increased general intellectual functioning, primarily via increased neurocognitive information processing speed. Also supporting the crucial role of white matter integrity in the P-FIT model is research by Nagy, Westerberg and Klingberg (2004) that demonstrated a significant relation between the maturation of white matter, functioning of the parietal and frontal cortices, and working memory performance (to be discussed in Level III of IM explanatory model below) between the ages of 8 and 18 years. White matter tract integrity and rate of development, this time increasing the efficiency of communication between brain regions primarily involved in reading (i.e., Broca's and Wernicke's areas), has also been suggested to be a fundamental brain mechanism involved in learning to read (Yeatman, Dougherty, Ben-Schar & Wandell, 2012). It is clear that white matter maturation and integrity "is correlated with development of specific cognitive functions" (Nagy et al., 2004, p. 1227).

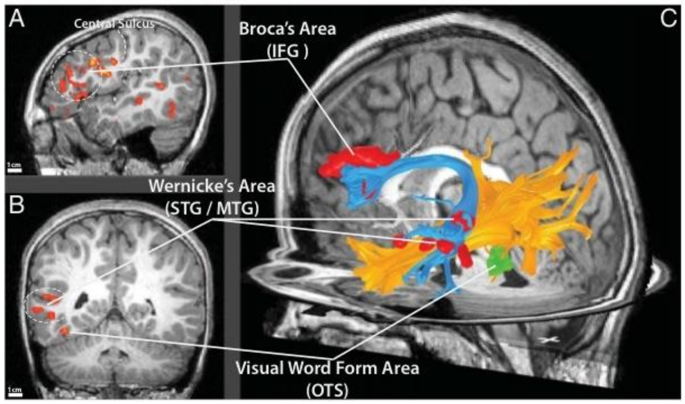


Fig. 1. Essential cortical circuits and white-matter connections for reading. (*A* and *B*) Blood oxygen level-dependent responses in a 10-y-old engaged in a rhyming task. In alternating 12-s blocks the subject judged if a pair of written words rhyme or whether two line patterns are the same. The subject's gray matter was segmented, and regions within the cortex with reliable task-related modulations ($P < 0.001$, uncorrected) were identified (colored overlay). A sagittal and coronal plane are shown to illustrate the phonological processing-related activations in the inferior frontal gyrus (IFG; Broca's area) and superior/middle temporal gyrus (STG/MTG; Wernicke's area) and the orthographic processing-related activation in the occipito-temporal sulcus (OTS). (*C*) Responsive voxels from Broca's area and Wernicke's area were rendered in 3D and displayed as surfaces within the brain volume (red). Two large fascicles, estimated with deterministic fiber tractography, are shown also. The arcuate fasciculus (blue) may carry phonological signals from the posterior temporal lobe to the inferior frontal lobe. The VWFA activation is rendered as a green surface. The ILF (orange) may carry signals from the VWFA to the anterior and medial temporal lobe. Fig. S7 shows the procedure used to identify the arcuate and ILF.

White matter integrity and intelligence
L Penke *et al*

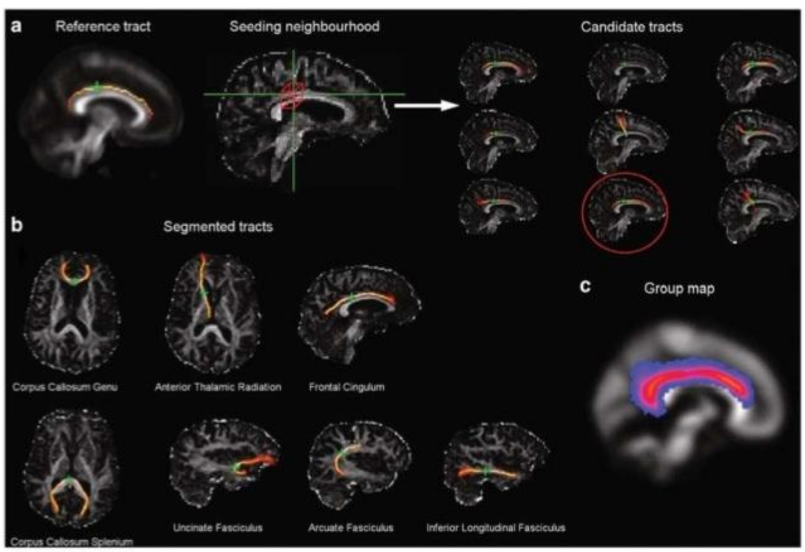


Figure 1. (**a**) Schematic diagram showing the probabilistic neighbourhood tractography processing pipeline for automatic tract segmentation. Given a pre-defined reference tract, in this case rostral cingulum, seed points are automatically placed in a neighbourhood surrounding a seed point transferred from standard space (red box). The tract that best matches the reference in terms of both length and shape (red circle) is chosen from this group of 'candidate' tracts. (**b**) Examples of the tracts segmented in this study for a representative subject. (**c**) A maximum intensity projection of a standard space group map of a segmented fasciculi-of-interest, in this case rostral cingulum, overlaid on an MNI white matter volume. Note the consistent segmentation of the tract across the cohort.

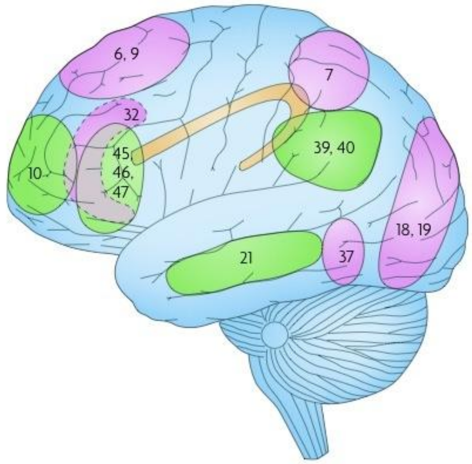


Figure 2 | **The loci of intelligence differences.** Based on a review of all the structural and functional neuroimaging literature that was available, Jung and Haier proposed the parieto-frontal integration theory of intelligence (P-FIT), which is arguably the best available description of how intelligence is distributed in the brain. The figure shows Brodmann Areas (BAs) involved in intelligence, as well as the arcuate fasciculus (shown in yellow) as a promising candidate for a white matter tract that connects the involved brain regions. BAs shown in green indicate predominantly left-hemispheric correlations and BAs shown in pink indicate predominantly right-hemispheric correlations with intelligence. Figure is modified, with permission, from REF. 60 © (2007) Cambridge University Press.

npg White matter integrity and intelligence
L Penke *et al*

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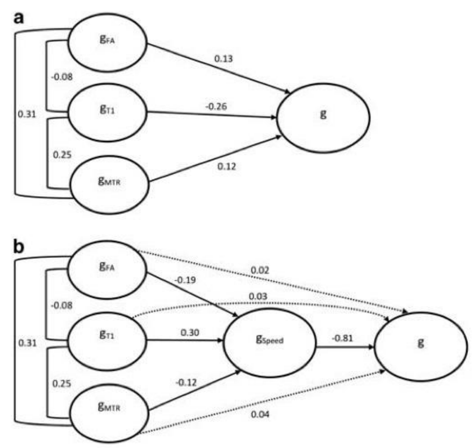


Figure 2. Results of SEM of the three white matter integrity factors, general intelligence, and information-processing speed. Only the latent variables are depicted. For full measurement models see Supporting Online Materials. All path estimates are standardised. (**a**) g_{FA}, g_{T1} and g_{MTR} (common latent factors each defined by their respective tractography estimate for all 12 tracts) are independently associated with general intelligence (g) ($\chi^2(755) = 1721.27$, CFI = 0.945, NNFI = 0.938, RMSEA = 0.055, SRMR = 0.054), explaining 10.0% of the variance. (**b**) Cognitive information-processing speed (g_{Speed}) mediates the association between the three latent white matter tract integrity factors and general intelligence. Note that higher values of g_{Speed} indicate slower (less favourable) information-processing speed. The model with solid lines fits the data well ($\chi^2(880) = 1900.894$, CFI = 0.943, NNFI = 0.936, RMSEA = 0.053, SRMR = 0.053, AIC = 36524.9, BIC = 37151.1). Additional direct paths from g_{FA}, g_{T1} and g_{MTR} to g (dotted lines) have negligible, non-significant path estimates and decrease model fit (AIC = 36530.1, BIC = 37168.5), indicating full mediation of the effect of the three white matter tract integrity indices on general intelligence by cognitive information-processing speed.

-

Evidence for the P-FIT model explanation of the *IM effect*. Compelling evidence for the above set of hypotheses and research findings comes from a study that investigated the *IM effect* on cognitive measures and electrocortical functioning in soldiers recovering from *blast related traumatic brain injury* (BRBI; Nelson, 2012). A summary of this studies details are presented in the **Call Out Box** on the next page.

As summarized in **Call Out Box**, It was concluded that the IM treatment produced better functional synchronization or connectivity between the frontal and parietal cortices (and possibly the thalamus) and built millisecond timing awareness and response capability (Nelson, 2012). This IM-specific study supports the above described Level I and Level II (see Figure 1) hypotheses that the *IM effect* may be due to increased neural efficiency, particularly more efficient functional synchronization, connectivity, and communication between important brain regions, especially those involved in the coordinated action of the default, salience, and central executive networks. **The study of soldiers with blast related brain injuries (Nelson, 2012) also provides support for the Level II model that specifically suggests that the P-FIT model of intelligence is consistent with the *IM effect* and, more importantly, IM technology may be improving the efficiency of the parietal-frontal brain network, a network believed to be critically involved in general intellectual functioning, working memory, controlled attention, and overall cognitive efficiency. It was also suggested that these improvements my reflect re-establishment of white matter connections for certain brain networks.**

Effects of IM on Cognition and Electrocoritcal Functioning in Recovery from Blast Related Brain Injury Study Summary (Nelson, 2012)[1]

Subjects: Forty-five subjects (18-55 years of age) with documented military blast related traumatic brain injury (BRBI) meet specific study inclusion and exclusion criteria. Subjects had to be greater than 3 months, and less than 5 years, post-BRBI. The subjects had to have documented BRBI and had to meet the DSM-IV criteria of either (a) postconcussional disorder or (b) mild neurocognitive disorder due to a general medical condition. Subjects were excluded if there was evidence of (a) pre-BRBI moderate or severe traumatic brain injury, (b) suicidal ideation or indications of other psychiatric conditions, (c) evidence of drug/alcohol dependence or abuse (c) current medication with benzodiazepines or narcotics, or (d) were in another drug or treatment trial. At the time of the preliminary report (Nelson, 2012), 100% of the subjects were male. The average number of BRBI's was 2.9 (standard deviation = 1.6). The average time since injury was 28.6 months (standard deviation = 23.9). The subjects were randomly assigned to an IM treatment group or a control group that received traditional brain injury rehabilitation treatment at a brain injury center for veterans. Thirty-six subjects had complete data at the time of the 2012 report, 18 of each in the IM and control groups. No statistically significant differences on the baseline assessment measures were reported.

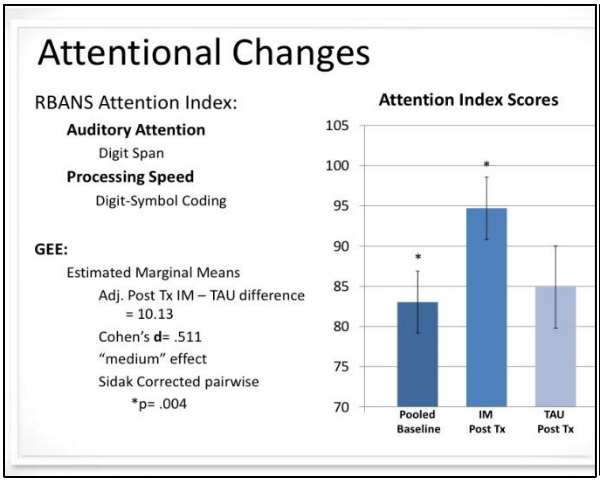
IM Treatment: Subjects received 13 different IM developed exercises at a tempo of 54 beats per minute. Complete treatment consisted of 15 sessions, each approximately 1 hour in duration with approximately 2,500 IM repetitions per session. The total IM repetitions across the 15 sessions was just over 37,000.

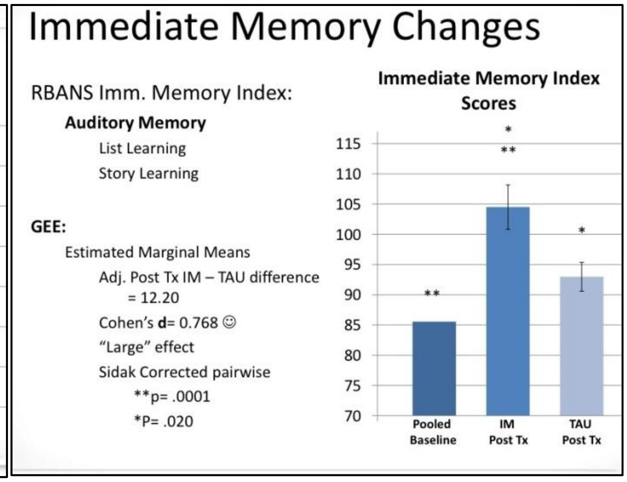
Methodology: Pre-post *neuropsychological testing* consisted of the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS; Randolph, 1998), processing speed and short term and working memory tests from the Wechsler Adult Intelligence Scale-Fourth Edition (WAIS-IV; Wechsler, 2008), as well as select measures from the Delis-Kaplan Executive Function System (DKEFS; Delis, Kaplan & Kramer, 2001).

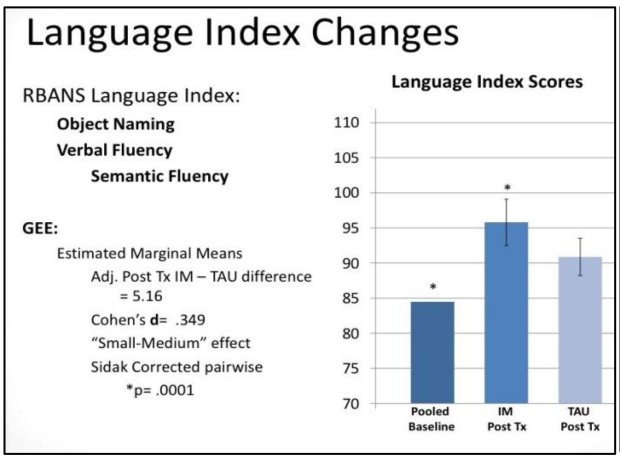
Electrocortical assessment consisted of 64-channel EEG electrocortical measurement of brain *event related potentials* (ERP's) during resting and event state activity. The event activity was a go/no-go task designed to measure decision and inhibition processes. ERP's were averaged over multiple trials with "noise" eliminated. The N100 (related to auditory attention and information processing) and P300 (related to learning and memory processing as well as being sensitive to attention) ERP wave form components wre evaluated. ERP wave forms were analyzed via independent components analysis (ICA), sample signal decomposition (ICA), and event related band power (ERBP) changes.

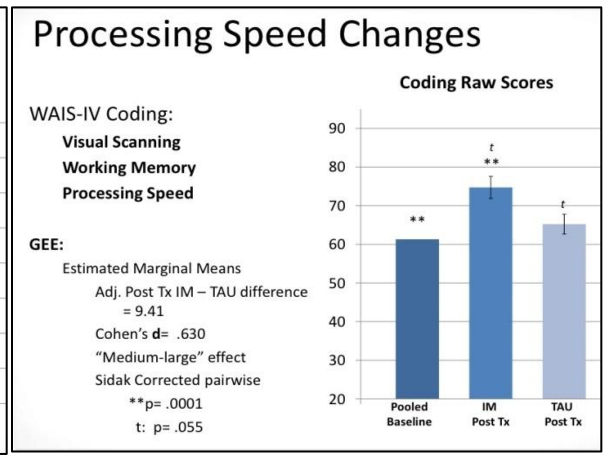
Findings: The IM treatment group demonstrated statistically significantly higher pre-post change scores on the neuropsychological assessment measures. The majority of *Cohen's d* effect sizes ranged from approximately .35 to .80, which are characterized as *medium* to *large* treatment effects. Across the different neuropsychological assessment variables, positive IM treatment effects were reported for 21 of the 26 outcome measures. It was concluded that for BRBI subjects, IM produced positive statistical and practically important larger treatment effects (than the control group) on immediate memory, processing speed, and sensory integration functioning. The EEG electrocortical measurement of the brain event related potentials (ERP's) of the IM and control subjects (when performing the go/no-go task) found the IM treatment group demonstrating increased ERBP activation in the frontal and right parietal cortices. This suggested better functional connectivity between these brain areas, as well as the thalamus.

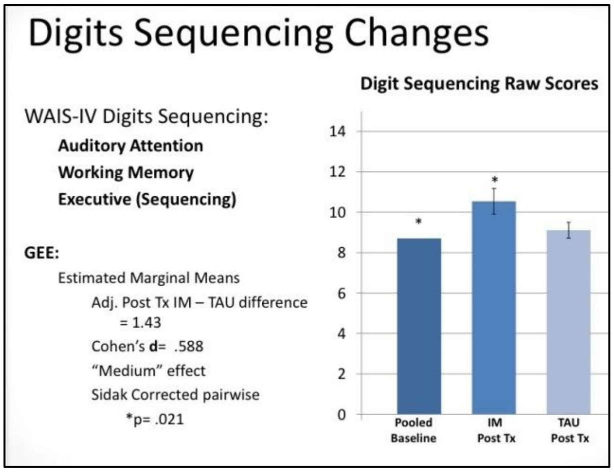
It was concluded that the IM treatment increased immediate memory, processing speed, and sensory integration in subjects with BRBI. In addition, the IM treatment produced better functional synchronization or connectivity between the frontal and parietal cortices. Brain plasticity was suggested via the building of millisecond timing awareness and response capability Nelson (2012) concluded that the IM treatment may result in (a) improved multi-sensory readiness, (b) more robust inhibitory networks, (c) better coordinated response production, (d) increased cortical endurance, and (e) possibly the re-establishment of white matter connections between brain networks.


Attentional Changes
RBANS Attention Index:
Auditory Attention
Digit Span
Processing Speed
Digit-Symbol Coding
GEE:
Estimated Marginal Means
Adj. Post Tx IM – TAU difference = 10.13
Cohen's d= .511
"medium" effect
Sidak Corrected pairwise
*p= .004
Attention Index Scores
105
100
95
90
85
80
75
70
*
*
Pooled Baseline
IM Post Tx
TAU Post Tx

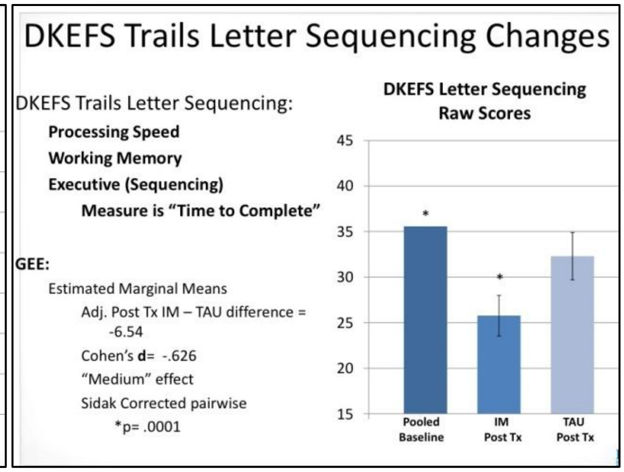

Immediate Memory Changes
RBANS Imm. Memory Index:
Auditory Memory
List Learning
Story Learning
GEE:
Estimated Marginal Means
Adj. Post Tx IM – TAU difference = 12.20
Cohen's d= 0.768 ☺
"Large" effect
Sidak Corrected pairwise
**p= .0001
*P= .020
Immediate Memory Index Scores
115
110
105
100
95
90
85
80
75
70
*
**
**
*
Pooled Baseline
IM Post Tx
TAU Post Tx


Language Index Changes
RBANS Language Index:
Object Naming
Verbal Fluency
Semantic Fluency
GEE:
Estimated Marginal Means
Adj. Post Tx IM – TAU difference = 5.16
Cohen's d= .349
"Small-Medium" effect
Sidak Corrected pairwise
*p= .0001
Language Index Scores
110
105
100
95
90
85
80
75
70
*
*
Pooled Baseline
IM Post Tx
TAU Post Tx

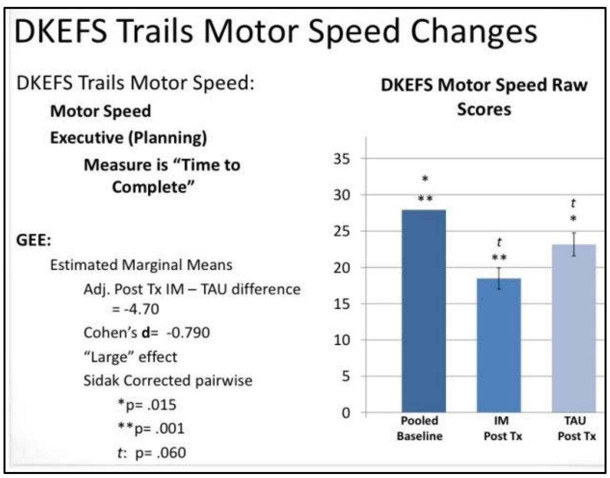

Processing Speed Changes
WAIS-IV Coding:
Visual Scanning
Working Memory
Processing Speed
GEE:
Estimated Marginal Means
Adj. Post Tx IM – TAU difference = 9.41
Cohen's d= .630
"Medium-large" effect
Sidak Corrected pairwise
**p= .0001
t: p= .055
Coding Raw Scores
90
80
70
60
50
40
30
20
**
t
**
t
Pooled Baseline
IM Post Tx
TAU Post Tx



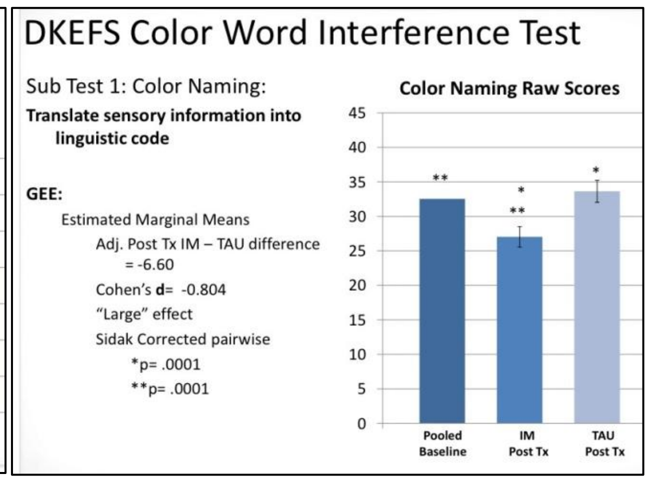
Digits Sequencing Changes
WAIS-IV Digits Sequencing:
Auditory Attention
Working Memory
Executive (Sequencing)
GEE:
Estimated Marginal Means
Adj. Post Tx IM – TAU difference = 1.43
Cohen's d= .588
"Medium" effect
Sidak Corrected pairwise
*p= .021
Digit Sequencing Raw Scores
0
2
4
6
8
10
12
14
Pooled Baseline
IM Post Tx
TAU Post Tx



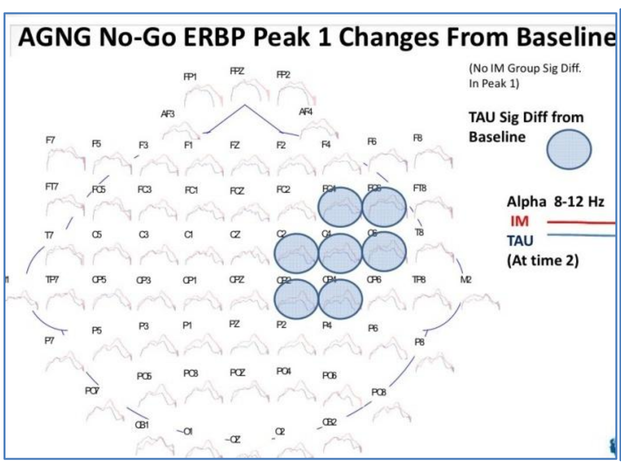
DKEFS Trails Letter Sequencing Changes
DKEFS Trails Letter Sequencing:
Processing Speed
Working Memory
Executive (Sequencing)
Measure is "Time to Complete"
GEE:
Estimated Marginal Means
Adj. Post Tx IM – TAU difference = -6.54
Cohen's d= -.626
"Medium" effect
Sidak Corrected pairwise
*p= .0001
DKEFS Letter Sequencing Raw Scores
15
20
25
30
35
40
45
Pooled Baseline
IM Post Tx
TAU Post Tx



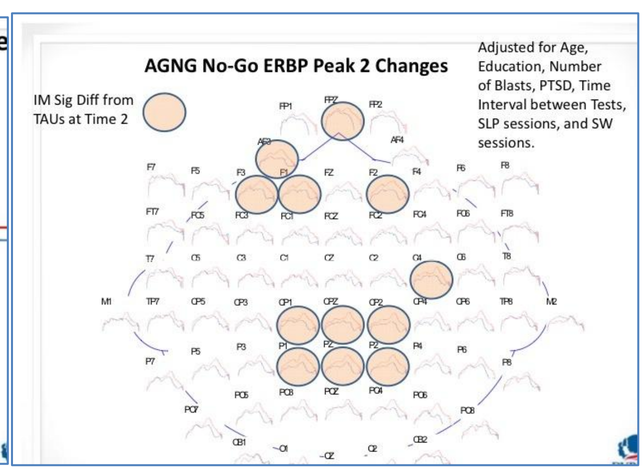
DKEFS Trails Motor Speed Changes
DKEFS Trails Motor Speed:
Motor Speed
Executive (Planning)
Measure is "Time to Complete"
GEE:
Estimated Marginal Means
Adj. Post Tx IM – TAU difference = -4.70
Cohen's d= -0.790
"Large" effect
Sidak Corrected pairwise
*p= .015
**p= .001
t: p= .060
DKEFS Motor Speed Raw Scores
0
5
10
15
20
25
30
35
Pooled Baseline
IM Post Tx
TAU Post Tx



DKEFS Color Word Interference Test
Sub Test 1: Color Naming:
Translate sensory information into linguistic code
GEE:
Estimated Marginal Means
Adj. Post Tx IM – TAU difference = -6.60
Cohen's d= -0.804
"Large" effect
Sidak Corrected pairwise
*p= .0001
**p= .0001
Color Naming Raw Scores
0
5
10
15
20
25
30
35
40
45
Pooled Baseline
IM Post Tx
TAU Post Tx

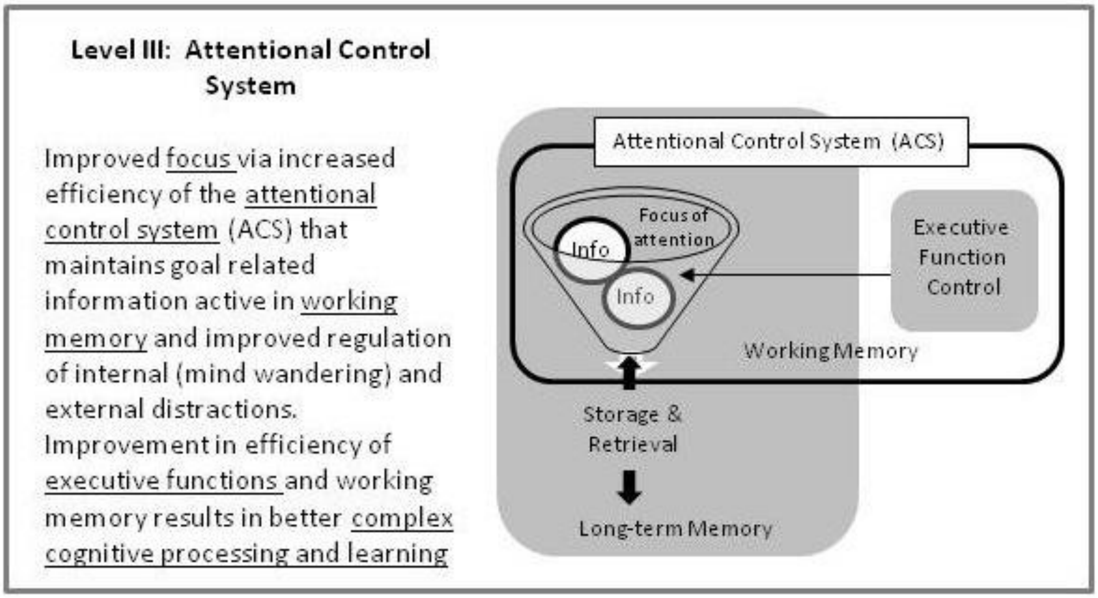


AGNG No-Go ERBP Peak 1 Changes From Baseline
(No IM Group Sig Diff. In Peak 1)
TAU Sig Diff from Baseline
Alpha 8-12 Hz
IM
TAU
(At time 2)



AGNG No-Go ERBP Peak 2 Changes
Adjusted for Age, Education, Number of Blasts, PTSD, Time Interval between Tests, SLP sessions, and SW sessions.
IM Sig Diff from TAUs at Time 2

Level III: Improvement of the Attentional Control System (ACS)



McGrew (2006) and Taub et al. (2007) were the first to present a conceptual cross-walk between the theoretical and empirical research regarding the major components of the PAM master internal clock and temporal processing (Level I) and contemporary cognitive information processing theories (Level III) when attempting to explain the *IM effect*. These researchers suggested that the *IM effect* was likely due to increased millisecond timing-based neural efficiency of the domain-general cognitive information processing mechanisms of *working memory*, *executive functions*, and *controlled or executive attention* (Level III in Figure 1).

Drawing on research suggesting a *temporal g* (general intelligence) cognitive mechanism, McGrew (2006) and Taub et al. (2007) further suggested that the domain-general positive *IM effect* was likely due to the improvement of general neural efficiency via improved resolution of the internal brain clock. Finally, these researchers hypothesized the involvement of certain brain structures (cerebellum, structures of the basal ganglia, striatum, dorsolateral prefrontal cortex, right parietal cortex) during IM performance. The overlap and convergence in the brain clock (Level I) and neurocognitive information processing (Level III) models is not surprising as "it is difficult to distinguish between the processing of timing per se, on the one hand, and attention and working memory processes, on the other, because these are closely interconnected in explicit time judgments" (Droit-Volet, 2013, p. 229).

McGrew (2012) has suggested that the primary mechanism by which working memory is enhanced by IM is the training of controlled attention and inhibition (Chuderski & Necka, 2012; Chun, Golomb & Turk-Growne, 2011; Engle, 2002; Eysenck & Derakshan, 2011; Posner, 2007). To stay "on target" (i.e., keeping the "information" circles inside the "focus of attention" cone at Level III in Figure 1) requires subjects 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 (wind-wandering) stimuli. According to McVay and Kane (2010), “mind wandering represents, in part, a failure of executive control…the occurrence of mind wandering is dually determined by the presence and urgency of automatically generated, personal-goal-related thoughts (from the default-mode brain network) in response to cures in the external and internal environment, as well as the ability—or inability—of the executive-control system to defend primary-task performance against interference from these thoughts” (p. 188).

Attentional capture is minimized by the process of *inhibition* (ignoring task irrelevant distractions—self-generated random thoughts or mind wandering). The constant IM millisecond-based feedback requires subjects to suppress attending to distracting external and internal stimuli. The subjects personal mind manager (i.e., executive functions) must constantly monitor the feedback and update immediate working memory so the subject 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 (Miyake, Friedman, Emerson, Witzki & Howerter, 2000). The role of executive functions in the attentional control system (ACS; Chuderski & Necka, 2012) is supported by research implicating the communication between the default, salience and central executive networks (Level II) for detecting and deflecting attentional capture by external stimuli and inhibiting the strong predisposition of the default network to induce spontaneous mind wandering.

The hypothesized relations between efficient working memory, attentional control, and cognitive performance outcomes (e.g., general intelligence, reading comprehension, SAT scores) has been supported in a number of contemporary studies. Across six experiments, Chuderski and Necka (2012) concluded that the ability to focus and control attention accounted for approximately 62% of subjects novel problem solving or fluid intelligence. They also reported that executive functions accounted for approximately 13 % of fluid reasoning. Unsworth et al. (2012) presented a model where working memory capacity impacted attentional control, which in turn had an effect on everyday attention failures, which in turn had a significant impact on SAT scores. Finally, Kane and McVay (2012) reported a model where reading comprehension was directly impacted by both working memory capacity and mind wandering (defined as task unrelated thoughts—*TUT’s*). These studies, which focused primarily on attentional control, mind wandering, and working memories impact on cognitive outcomes, reinforce a large body of intelligence research which has suggested that working memory, when defined more globally, has a strong causal and direct influence on general intelligence and fluid reasoning (Ackerman, Beier & Boyle, 2005; Colom, Rebello, Palacios, Juan-Esinosa & Kyllonen , 2004; Conway, Kane & Engle, 2003; Kyllonen & Christal, 1990; McGrew, 2005). The theoretical and empirical link between efficient working memory capacity and cognitive performance is clear. Even more intriguing is the conclusion of some researchers that working memory capacity may be nothing more than executive or controlled attention (Engle, 2002; Kane, Bleckely, Conway & Engle, 2001).

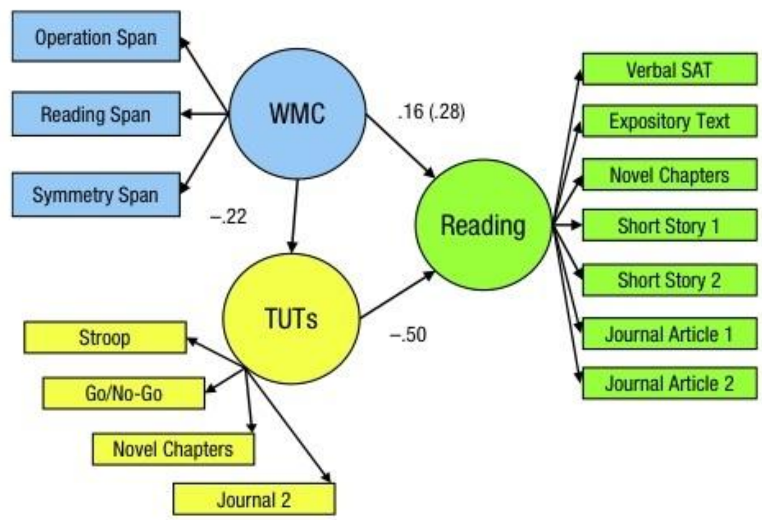


Fig. 2. A latent-variable model depicting the relation between working memory capacity (WMC) and reading-comprehension test performance (Reading), with mind wandering (i.e., task-unrelated thoughts, or TUTs) as a partial mediator. Latent factors are depicted in circles. Values represent the strength of the paths, or associations, between latent variables (all are statistically significant); the value in parentheses reflect the strength of the association between WMC and reading comprehension without the mediating effect of TUTs. Observed variables contributing to each factor are depicted in rectangles. Arrows between latent factors represent the modeled direction of their associations. The observed variables in blue rectangles represent scores on an operation span task (a measure of verbal WMC), a reading span task (a measure of verbal WMC), and a symmetry span task (a measure of visuospatial WMC). The observed variables in yellow rectangles represent TUT rates during a numerical Stroop task, a go/no-go attention task, a novel-chapters reading task, and a second journal-article reading task. The observed variables in green rectangles represent verbal SAT score, accuracy on inference-based tests about two brief expository texts, accuracy on comprehension questions during the novel-chapters reading task, and accuracy on comprehension questions following two short-story reading tasks and two journal-article reading tasks. Adapted from "Why Does Working Memory Capacity Predict Variation in Reading Comprehension?" by J. C. McVay and M. J. Kane, 2012, *Journal of Experimental Psychology: General, 141*, p. 312. Copyright 2012, American Psychological Association. Adapted with permission.

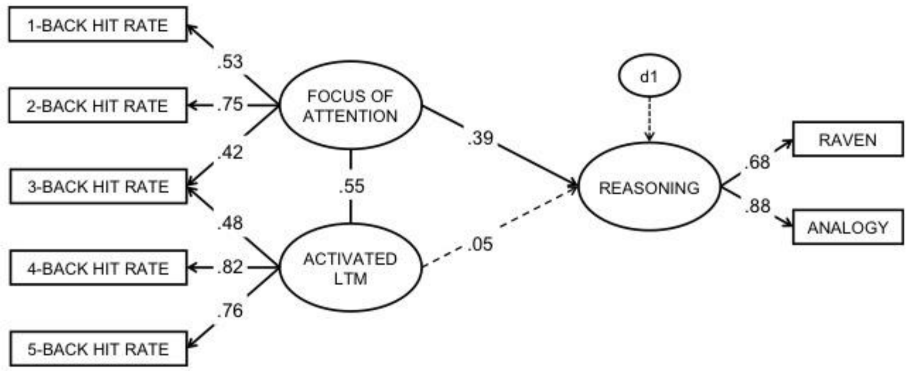


Figure 1. The structural equation model for Experiment 3, relating the focus of attention and activated long-term memory (LTM) exogenous latent variables to the fluid reasoning endogenous latent variable. Boxes represent manifest variables (see explanation in the text). Large ovals represent latent variables, while the small oval represents a disturbance term. Values between ovals and boxes represent relevant standardized factor loadings (all *ps* $< .01$). Values between ovals represent path coefficients among latent variables: The solid lines represent *ps* $< .001$, while the dashed line represents $p > .05$.

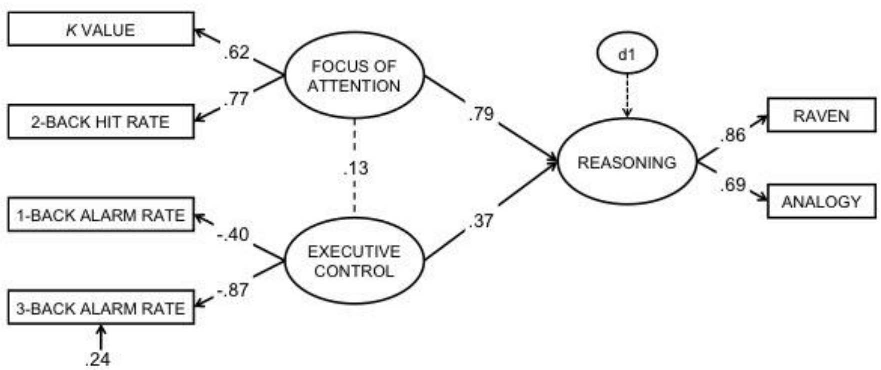


Figure 4. The structural equation model for the 2-back group of Experiment 5, relating the focus of attention and executive control exogenous latent variables to the fluid reasoning endogenous latent variable. Boxes represent manifest variables (see explanation in the text). Large ovals represent latent variables, while the small oval represents a disturbance term. Values between ovals and boxes represent relevant standardized factor loadings (all *ps* $< .01$). Values between ovals represent path coefficients among latent variables: The solid lines represent *ps* $< .001$, while the dashed line represents $p > .05$. Note that because of the negative variance found in the initial model, the error parameter for the 3-back false alarm rate was fixed at a value of 1 minus its reliability.

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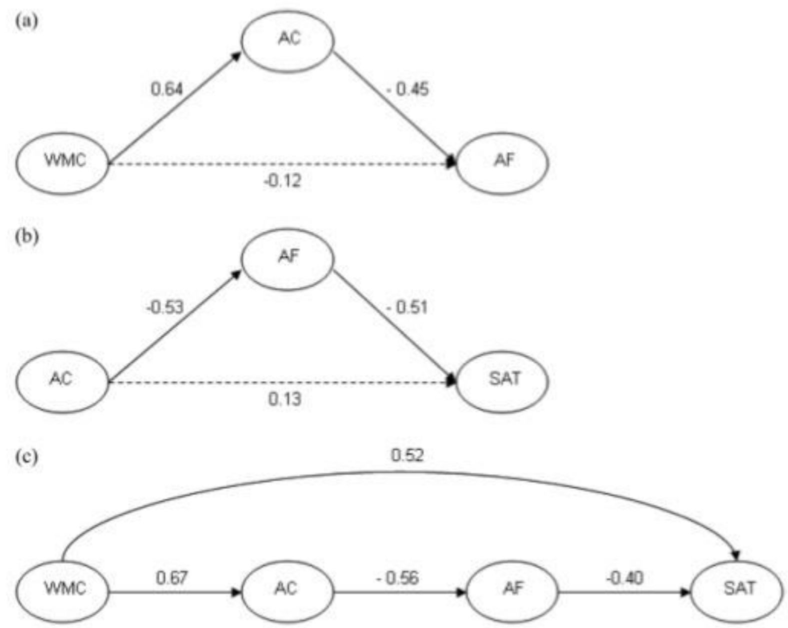

Figure 3. (a) Structural equation model for working memory capacity (WMC), attention control (AC), and everyday attention failures (AF). (b) Structural equation model for AC, AF, and SAT scores. (c) Structural equation model for WMC, AC, AF, and SAT scores. Single-headed arrows connecting latent variables (circles) to each other represent standardized path coefficients indicating the unique contribution of the latent variable. Solid lines are significant at the $p < .05$ level, and dotted lines are not significant at the $p < .05$ level.

The evidence presented above (Level II), and the IM blast-related brain injury research of Nelson (2012) in particular, supports much of the early IM explanatory hypotheses of McGrew (2006) and Taub et al. (2007). More important**, the Level II research summarized above suggests that IM technology may be improving brain network communication, especially within the major brain networks at the core of the P-FIT model of general intelligence.**[6] The overlap in the importance of the parietal-frontal circuit in both the brain clock timing research (Level I) and research regarding the importance of domain-general neurocognitive mechanisms (working memory, attentional control, inhibition and executive functions) significantly associated with general intelligence (Level III) is key to McGrew's (2012) three-level explanation of the *IM effect* (see Figure 1). The strong evidence for a causal link between working memory and general cognitive outcomes is consistent with the domain-general working hypothesis for the *IM effect*. At Level III, this domain-general cognitive

[6] Other brain networks involved in other domains (e.g., reading, motor performance, gait, etc.) most likely also benefit from this hypothesized increased in efficient brain network communication. In this text the primary focus is on the parietal-frontal network, and its role in increased attentional control, working memory, executive function and general intelligence, as this is the domain with the greatest amount of extant research and is the domain where the most likely important IM effects are noted (i.e., focus and attentional control).

mechanism is manifested in the form of working memory, which involves the constructs of mind wandering, attentional control, and executive functions. At Level I the domain-general cognitive mechanism is hypothesized to be in the form of improved brain clock speed or temporal resolution.

In summary, **the most important Level III (see Figure 1) IM training outcome (but not the only outcome) is improved focus via increased efficiency of the attentional control system (ACS) that maintains goal related information active in working memory in the presence of internal (mind wandering) and external distractions. Improvement in efficiency of executive functions and working memory results in more efficient complex cognitive processing and learning.** These Level III measurable neurocognitive outcomes are believed to be explained by the underlying (and unobservable) brain and neurocognitive mechanisms invoked during IM training as outlined in Level I and II of Figure 1.

Summary

IM research has demonstrated positive treatment effects across a variety of human performance domains and in a number of different clinical disorders. The diversity of domains positively impacted suggests that IM is impacting a domain-general brain-based neurocognitive mechanism or sets of mechanisms.

The *three-level explanatory model of the IM effect* (McGrew, 2012) presented in Figure 1 is currently the best working model for explaining the science behind the *IM effect*. Briefly, IM technology is believed to improve the resolution and efficiency of an individual's internal brain clock(s) and temporal processing. In turn, this increases neural efficiency which is hypothesized to result in more efficient brain connectivity, communication, and synchronization via increased integrity of the brains white matter tract communication system, producing more efficient communication between critical brain networks. In particular, research and theory suggests that IM technology may be increasing the efficacy of the parietal-frontal brain network, the brain network most associated with general intellectual functioning, working memory, controlled attention and executive functions.

Although not discussed here, brain networks involved in other performance domains (e.g., reading, motor performance, gait, etc.) most likely also benefit from the above hypothesized explanation of increased efficiency in brain network communication. In the above explanation the primary focus was on the parietal-frontal network and its role in increased attentional control, working memory, executive functions and general intelligence. This focus was deliberate as these domains are those with the greatest amount of extant research and are the domains where the most important IM effects will likely be noted (i.e., focus and attentional control). It is believed that the positive IM effects demonstrated in other domains, such as better motor coordination, speech and language functioning, stroke recovery, etc., result from similar increased brain communication efficiency and synchrony between brain regions and networks, specifically those more related to motor functions (e.g., supplementary motor area, cerebellum).

The three-level hypothesized model described here is a *general explanatory framework* for explaining positive *IM effects* in multiple human performance domains. The proposed model draws from a broad and diverse set of contemporary research from multiple disciplines, such as cognitive psychology, neuropsychology, neuroscience, neurology, molecular psychology, biological psychology, the psychology of music, and the study of human intelligence. **The three-level model described here can also be viewed as an IM-free integration of research and theory that explains the relations between the temporal processing (temporal *g*) of the human brain clock (s), brain regions and networks, brain network communication and synchronization (the parietal-frontal integration theory of intelligence [P-FIT] in particular), and the neurocognitive constructs of controlled attention (focus), working memory, and executive functioning.**

Additional research is needed to verify the current explanatory model, evaluate its utility to explain positive *IM effect* research in multiple domains, and to suggest necessary revisions and extensions.

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