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Working Memory: Building Blocks of Intelligence or an Incomplete Model?

Towards a Model of Enhanced Working Memory Informed by Multiple Intelligences Theory

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Abstract:

Working memory (WM) is associated with general intelligence as a measure of basic cognitive skills with consequences for academic achievement and life success. Cognitive training programs and educational treatment plans in schools to remediate WM deficits have had mixed results. Researchers question their efficacy at enhancing intelligence or promoting lasting cognitive ability. A major impediment to effectiveness is limited transferability of trained skills to everyday life. The basic model of WM and its relationship to human intelligence and as a basis for educational cognitive neuroscience is limited by a narrow description of essential cognitive abilities. This review of cognitive and neuroscience literatures reveals support for an enhanced model of WM aligned with multiple intelligences (MI: Frames of Mind, Gardner, 1983/1993, Basic Books). MI provides a broad description of intelligence that includes general intelligence as convergent aspects of logical-mathematical and linguistic intelligences. Neuroscience evidence indicates basic WM memory is aligned with visual-spatial, linguistic and intrapersonal intelligences. An enhanced model of WM includes the logical, musical and kinesthetic intelligences. Further research is required to determine the role of interpersonal and naturalist thinking for attention and mental processing. Implications for integrating MI-inspired cognitive training activities into personalized, strength-based educational programs are discussed.

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The concept of intelligence is both powerful and problematic on many levels. Despite the inability of psychologists to agree on a definitive definition (Barbey, 2017; Boring, 1923; Hunt and Jaeggi, 2013), the notion of a single intelligence is deeply rooted in the scientific literature as well as in popular culture as evidenced by hundreds of intelligence “tests” on the worldwide web. The idea that a single test score can account for much of life's success has great intuitive appeal as well as scientific usefulness. In the early 1900s, the use of several ability tests to determine a person's intelligence score represented an advance over questionable strategies such as phrenology and personal testimonials (Gould, 1981; Herrnstein and Murray, 1994; Ravitch, 2000).

Intelligence tests came along at just the right time to join cultural transitions from agricultural and industrial eras to the scientific revolution to the information age. IQ scores provided “hard data” to bolster the field of psychology that was emerging from the realm of philosophy into a respectable scientific endeavor. However, after half a century of research, the scientific validity of IQ came under serious attack in the 1960s and 1970s when many western cultural institutions and assumptions were being re-examined in light of social-cultural criticisms (Block and Dworkin, 1976; Herrnstein and Murray, 1994). Numerous alternative theories of intelligence have been proposed but few have survived in the minds of theorists and or impacted education broadly (Ravitch, 2000; Stankov, 2017).

These attacks on general intelligence (g) and its testing in schools resulted in the diminished value of the IQ score with greater emphasis on cognition and learning styles (Sousa, Tomlinson, 2018). Educational theorists can securely investigate cognitive abilities and information processing while classroom teachers comfortably discuss students' learning styles. Today, intelligence is rarely discussed directly, but instead it has gone underground while students continue to be “streamed” in classrooms and schools organize students according to their academic or cognitive ability.

While the concept of intelligence has fallen into disfavor, the idea of working memory (WM) has grown in scientific respectability and prominence (Baddeley, 1986). Some researchers claim that the two concepts are nearly indistinguishable (Colom, et al., 2010; Kyllonen and Christal, 1990) but this is not a universal view (Ackerman, Beier, and Boyle, 2005). Early models of intelligence and working memory focused on a few simple components

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hypothesized to be the fundamental building blocks of general intelligence (Baddeley and Hitch, 1974). In fact, WM tests closely resemble mini-IQ scores with a visual subtest (associated with Performance IQ) and Digit Span (Verbal attention and mental processing) (Conway, Kane and Engle, 2003).

School psychologists make use of both IQ scores and working memory tests as part of their student evaluations for learning disabilities and difficulties, but this use has also been questioned (Sternberg and Grigorenko, 2002). An advantage of the working memory concept is that it lacks the perceived cultural bias and stigma associated with an intelligence score. A second advantage is that it has been the subject of much experimental investigation by cognitive and neuroscientists. In fact, the improvement of working memory has come to be a target of many forms of cognitive training for people young and old (Gathercole, Dunning and Holmes, 2012; Jaeggi, et al., 2008). In a real sense, working memory has resurrected the idea of intelligence but by a more respectable name. Is this progress or a problem? As with any question about a complex topic, the answer is some of bothprogress, but with problematic limitations.

Working memory (like a mini-IQ) is limited in its description of essential human abilities. This restricted range results in reduced capacity to be of educational value even though there are practical problems associated with working memory impairments (Gathercole and Baddeley, 1993). Like with IQ tests, merely ranking students according to WM scores (from defective to superior) has little instructional value (Alloway, et al., 2009). Classroom teachers find such rankings to be detrimental and lacking in ecological validity. Likewise, test scores that highlight a few cognitive deficits may overshadow important cognitive strengths that could be useful for treatment recommendations. Teachers can plainly see the great variety of cognitive profiles facing them in the classroom even among those with similar IQ scores.

Teachers have resorted to using a variety of learning style terminologies to get a handle on these differences. Such theories are of questionable value because there may be more than 80 different learning style theories (Sousa and Tomlinson, 2018). Thus, it is unclear what a teacher means when she describes a student as being a “right brained thinker”, for example. Learning style theories tend to conflate personality preferences with cognition while maintaining the conventional assumption that what a student does in math class is “real intelligence.”

It came as a surprise when teachers around the world responded enthusiastically to Howard Gardner's theory of multiple intelligences (MI). His seminal book Frames of Mind, written in 1983 with psychologists in mind, provides a wealth of scholarly explication for the existence of seven intelligences but little explicit direction for classroom instruction. MI provides a rich and dynamic description of diverse abilities that are evident in every classroom and community. MI theory bridges between many realms of scholarship and yet also offers a powerful lens and language for educators to understand their students' profile of abilitiesnot merely preferences or interests. MI was viewed as a gift to students who were marginalized because their true abilities were not captured by standardized testing, such as artists, poets, humanitarians and animal behaviorists, etc. MI continues to influence educators at every level more than 35 years after its debut (Chen, Moran and Gardner, 2009).

Unfortunately, MI theory has remained more of a “framework” than a mature scientific theory while the fields of cognitive science and neuroscience have exploded. The following discussion explores how three important theories rooted in neuroscience WM, MI and g - can be integrated to create a richly detailed and useful description of human abilities. This discussion may then serve to inspire personalized, strength-based models of educational cognitive neuroscience as sketched in Part 3.

The following discussion examines in detail how theories of working memory have evolved and compares this evolution to the alternative view of multiple intelligences. An enhanced model of working memory is proposed. If the idea of intelligence is to be resurrected, it needs to be useful in the classroom as well as theoretically coherent and aligned with neuroscientific evidence. Thus, this discussion ends with a brief (and admittedly, preliminary) review of cognitive training programs that are aligned with MI theory.

Part One describes the theoretical relationship among working memory, general intelligence and the multiple intelligences. Part Two provides a review of neuroscience evidence supporting this theoretical model of enhanced working memory. Part Three describes educational implications and future directions for using MI-inspired working memory to enhance cognitive achievement and life success.

WM Implications for Academic Achievement and Intelligence

The concept of working memory has had a long and influential history in the fields of cognitive psychology and cognitive neuroscience (Baddeley and Hitch, 1974; Baddeley, Eysenck & Anderson 2015). Working memory has had several definitions including “…a system that is used for temporary storage and manipulation of information and that is involved in many higher cognitive functions…” (Smith and Jonides, 1999, p. 1657). In the quest to find the building blocks of intelligence, cognitive psychologists developed an information processing model to postulate that higher order abilities rest upon a foundation of a few basic cognitive skills embodied in working memory (Oberauer, et al., 2008). If this hypothesis is correct then increasing a person's intelligence would involve devising exercises that improve these basic cognitive skills (Colom, et al., 2010; Kyllonen & Christal, 1990).

Achieving this ambitious goal has proven to be elusive (Shipstead, Hick and Engle, 2012). Creating effective training tasks depends upon having a strong correspondence between working memory and the description of intelligence as an outcome measure. Given that the most common models of working memory include basic elements of IQ tests (Conway, Kane & Engle, 2003), it would seem to be a matter of directly matching training tasks to these basic cognitive elements. This approach may sound logical and simple, but the reality of this model and its effectiveness are uncertain (Colom, et al., 2010; Baddeley, Eysenck and Anderson, 2015; Gathercole, Dunning and Holmes, 2012; Shipstead, Redick and Engle, 2010; Shipstead, Hicks & Engle, 2012; Malby-Lervag and Hulme, 2013; Jaeggi, et al., 2011).

A main problem has been summed up by Colom, et al., "Participants in an improvement program may show increased performance on particular mental tests but, transfer or generalizability usually fails" (2010, p. 497). A possible source of the problem is that "…a wide range of tasks are still being used to measure WM and it is not clear how all these tasks relate to one another or to g (general intelligence)" (Conway, Kane and Engle, 2003, p. 550).

A problem may be the assumption that general intelligence is the single most important factor in academic/school/life success. Numerous studies have found that non-cognitive factors such as self-regulation, perseverance, resilience, and motivation can be more highly correlated with school achievement than general intelligence (Checa and Rueda, 2011; Duckworth and Carlson, 2013; Duckworth and Seligman, 2005; McClelland, et al., 2007).

Originally, investigators identified a strong correlation between WM test results and other real-world achievements such as reading, math, ADHD, problem solving, and intelligence (Tillman, Nyberg and Bohlin, 2008; Gathercole and Baddeley, 1993). Kyllonen and Christal concluded WM was highly correlated with reasoning ability (r=.80 - .90) and that "…reasoning ability, or general fluid intelligence…is at the core of what is ordinarily meant by intelligence…the primary determinant of the degree to which a person benefits from instruction" and thus "…limitations in working-memory capacity are responsible for the difficulties of learning new facts" (1990, p. 392) (Carroll, 1989; Gustafsson, 1984).

However, the strength of the correlation between WM and intelligence has been called into question as investigators have conducted more nuanced research into WM and its constituent components and outcomes. Oberauer, et al. question the adequacy of WM as a predictive measure of intelligence because it does not assess the person's capacity for relational integration which is a stronger predictor of reasoning ability. "Relational integration refers to the ability of building new relations between elements and thereby creating structural representations" (2008, p. 641) (Waltz, Knowlton and Holyoak, 1999).

The adequacy of a brief measure including just a few cognitive skills such as WM tests to predict intelligence has also been doubted by Ackerman, et al. (2005) and Davies, Jones, and Taylor (1984). "It is not possible to identify g with any single test … such as WM … we were able to reject a model in which WM measures and ability measures were captured by a single factor in favor of a model with separate g and WM factors though the estimated correlation between WM and g latent factors in this model was .50 (Ackerman, et al., 2005, p. 52).

Ackerman and colleagues found that "WM measures are significantly more highly correlated with narrow measures of information-processing speed and accuracy than they are with a measure most closely identified with nonverbal reasoning or fluid intelligence" (2005, p. 38). Their findings supported the conclusion that the relationship between general intelligence and WM was "modest at best" and that WM was a better measure of lower order cognitive abilities because it does not adequately sample the range of executive control attention associated with individual differences in intelligence.

Multiple Intelligences Theory Includes General Intelligence and Working Memory

While cognitive scientists have addressed the problem of enhancing cognitive functioning by searching for a few general principles or skills, Howard Gardner approached the problem from a different direction. He offered a rich and multifaceted perspective on human intelligence that highlights a full range of abilities that contribute to the creation of civilization. MI theory does not question that the skills embedded in IQ are important and modest predictors of academic achievement (generally correlated at around r=.40 - .60) (Sternberg & Grigorenko, 2001, p. 4). In fact, cognitive abilities essential to IQ are represented by the logical-mathematical and linguistic intelligences. MI argues that g is an inadequate as a complete model of the rich array of abilities embodied in human intelligence in everyday life.

This more expansive model of intelligence is based on a simple yet profoundly unique definition: "…intelligence is the ability or set of abilities that allows people to solve problems and fashion products that are of value in one or more cultures" (1993a). At first, seven distinct forms of "relatively independent" intelligences were described: linguistic and logical-mathematical (associated with academic achievement and IQ), visual-spatial, kinesthetic, musical, and two forms of personal intelligence interpersonal and intrapersonal. Based upon further evidence an eighth intelligence, naturalist, was added to the list in 1999. See Table 1 and Supplemental Information 1 for detailed definitions and sample careers.

Table 1. Multiple Intelligences Core Cognitive Units and Neural Correlates (Shearer and Karanian, 2017)

Intelligences	Core Cognitive Units	Primary Regions	Sub-regions
Interpersonal	-Social Perception -Interpersonal Understanding -Social Effectiveness -Leadership	Frontal Temporal Cingulate Parietal	Medial-Temporal Amygdala Dorsolateral PFC Anterior Cingulate Superior Temporal Sulcus
Intrapersonal	-Self-Awareness -Self-Regulation -Executive Functions -Self-Other Management	Frontal Cingulate Temporal Parietal Subcortical	Prefrontal-Cortex Anterior Cingulate Dorsomedial PFC Lateral Prefrontal Ventromedial
Logical-Mathematical	-Mathematical Reasoning -Logical Reasoning	Frontal Parietal Temporal	Prefrontal Intraparietal Sulcus Inferior Parietal Lobule
Linguistic	-Speech -Reading -Writing -Multimodal Communication of Meaning	Temporal Frontal Parietal	Superior Temporal Gyrus Inferior Frontal Gyrus Broca's Area Posterior Inferior Frontal Gyrus
Spatial	-Spatial Cognition -Working with Objects -Visual Arts -Spatial Navigation	Frontal Parietal Temporal Occipital	Premotor Cortex Motor Cortex Medial Temporal Prefrontal
Musical	-Music Perception -Music and Emotions -Music Production	Frontal Temporal Subcortical Cerebellum	Superior Temporal Gyrus Primary Auditory Cortex Premotor Cortex Basal Ganglia Supplementary Motor
Kinesthetic	-Body Awareness/Control -Whole Body Movement -Dexterity -Symbolic Movement	Frontal Parietal Subcortical Cerebellum	Motor Cortex Primary Motor Cortex Premotor Cortex Basal Ganglia
Naturalist	-Pattern Cognition -Understanding Living Entities -Understanding Animals -Understanding Plant Life -Science	Temporal Subcortical	Superior Temporal Sulcus Amygdala Brainstem Thalamus Midbrain Basal Ganglia

Note. Eight forms of intelligences are described by Gardner with several core cognitive components per intelligence. Each intelligence (as well as constituent components) are aligned with specific patterns of neural activation.

A limitation of MI theory is that it has not grown to account for many of the general cognitive capacities extensively studied by both cognitive and neuroscientists such as attention, memory, problem-solving, task management, and processing speed. Gardner wrote sparingly about how such proposed "general capacities" may or may not interact with the multiple intelligences (1993a, p. 280 285). Further research into these relationships was not conducted as the fields of cognitive science and neuroscience advanced. While MI theory was impacting educators around the globe, cognitive science progressed unaware of (or ignoring) the existence of MI theory as an alternative to unitary intelligence.

This lack of integrative research is unfortunate given that MI theory has its roots in both neuroscience and the cognitive sciences. Perhaps even more consequential is the resulting disconnect between the fields of education and cognitive neuroscience where the conceptual tools, terminologies, and behavioral interventions are vastly different. This gap was so wide that it prompted one leading psychologist to describe it as a "bridge too far" (Bruer, 1997). Bruer's view was that our understanding of neural processes is too limited to effectively guide educational decisions and designs.

This gap has narrowed recently as neuroscientists have grown more sophisticated in the design of their brain - behavior studies. Neuroscientists are now able to draw tighter connections between lab results and everyday cognitive behaviors thus improving their interpretability. The reverse has not been true. The real-world complexity of classroom behaviors continues to be difficult to untangle in neural models. However, MI theory offers one promising model that is rooted in neural evidence that can bridge between the practical needs of educators and behavioral specifics required by neuroscientists. As Gardner describes it, "To the extent that one wants to model faithfully what the nervous system is doing, it is appropriate to focus on the smallest possible modules that can be related to specific behavior… On the other hand, if one seeks a framework relevant to educators or policy makers in the field of human development, then it is important to posit modules at the levels of analysis employed in every-day discussion" (1993a, p. 284).

While the gap between the neuroscience lab and the classroom may be narrowing, the emerging field of educational cognitive neuroscience continues to struggle to establish itself as a rigorous science that can make practical contributions to school psychologists, instruction and curriculum. Some researchers have considered MI theory to be something of a neuromyth (Hale, et al., 2016; Tokuhama-Espinosa, 2010) because of its slim reliance on brain research and unexpected popularity among educators. However, a wealth of neuroscience evidence has recently described complex neural frameworks underlying each of the intelligences (Shearer and Karanian, 2017). These MI neural architectures can distinguish significant neural differences among three ability groups: skilled, typical, and impaired for each of the intelligences (Shearer, in press). These models also describe detailed neural circuitries for core cognitive components within each of the multiple intelligences (Supplemental Information 3). An examination of 97 resting state neural studies found that each of the eight intelligences have coherent functionally connected neural frameworks aligned with previous research findings (Shearer, 2017).

Of particular importance, the neural regions underlying general intelligence (Shearer and Karanian, 2017) are the same as those associated with the logical-mathematical and linguistic intelligences. This is as predicted by MI theory where IQ is primarily associated with the convergent problem-solving aspects of these two intelligences (Gardner, 1999). These data provide extensive evidence for the integration of MI with general intelligence rather than as mutually exclusive descriptions of human abilities. A summary of research is presented in Supplemental Information 9.

The Basic Working Memory Model Matched to MI

Table 2 presents the basic WM model as originally described by Baddeley (1974, 2015) and others. These basic WM components are matched with several of the multiple intelligences that are related theoretically.

Visuospatial WM tests often use graphic arrays of dots or other black and white designs to activate visuospatial attention and immediate memory (Alloway, 2007). This is a direct connection with the visual aspect of Gardner's description of visual-spatial intelligence. Later neuroscientists distinguished between the visual and spatial aspects in the brain's neural circuitry for working memory (Smith and Jonides, 1997; Smith and Jonides, 1999; Baddeley, Eysenck and Anderson, 2015). Visual spatial tasks are also included in most tests of general intelligence (g, or IQ) (Stanford-Binet, 2001; Weschsler, 1981). These involve copying or solving increasingly complex design and construction tasks. MI theory includes such visual-spatial logical problem-solving skills but in addition includes tasks of visual-spatial creativity requiring inspiration, intuition, and imagination such as sculpture, crafts, works of art, fashion design, or fantasy.

Verbal WM tests include the presentation of words or numbers that the respondent must repeat either in order or reversed (Alloway, 2007). Sometimes these words are presented orally or in written form. These tasks are not assessing mathematical skills but instead verbal attention span. Verbal skills (both speech and written) are core aspects of linguistic intelligence according to MI theory. These verbal and digit span tasks are included in many IQ tests (Weschler, 1981) as fundamental elements of verbal (and performance) IQ scores. In MI theory, linguistic intelligence includes both academic skills (reading and writing) as well as everyday speech (story-telling, persuasion) and creative pursuits such as poetry, novels, and science fiction.

Less obvious are connections between MI and WM's Central Executive that does the mental processing for the visuospatial and verbal contents. Gardner (1993a) is ambivalent about the existence of a general mental processor (p. 283) but alludes to the powers of cross intelligence management embedded in the intrapersonal intelligence "…the individual's sense of self as a kind of second-level regulator…that can, as part of its "duties," come to understand and to modulate an individual's other capacities" (p. 275).

Table 2. Basic Components of Working Memory Matched with Multiple Intelligences

Working Memory – Basic Components Matched to Multiple Intelligences		
Component	**Description**	**Multiple Intelligences Correlates**
Short Term Memory	"… working memory comprises a controlling Central Executive system aided by a number of slave systems, with access to passive storage… Articulatory Loop… and the Visuo - spatial Sketchpad components…" (p. 406, Baddeley, 1986)	Each intelligence has its own symbol and memory systems. ". …the normal human being is so constituted as to be sensitive to certain informational content: when a par ticular form of information is presented, various mechanisms in the nervous system are triggered to carry out specific operations upon it. And from the repeated use of, elaboration of, and interaction among these various computational devices, eventually flow forms of knowledge that we would readily term "intelligent… building upon "dumb" computational capacities, we may still end up with intelligent and even highly creative behavior" p. 279 Gardner, 1993a
Verbal	Phonological loop: …to hold verbal and acoustic information using a temporary store and an articulatory rehearsal system (Baddeley, 2010)	**Linguistic:** -mental verbalization -receptive language understanding -oral speech -reading -writing
Visuospatial	Visuospatial sketchpad … fractionable into separate visual, spatial and possibly kinaesthetic components, (Baddeley, 2010)	**Visual-spatial:** -mental visualization -visual perception -three-dimensional objects -spatial awareness
Central Executive Domain-General	"The capacity to perform more complex memory activities that include a substantial processing component are ascribed to the central executive, a limited capacity system responsible for several functions including the storage and retrieval of information, dir ecting the flo w of information through the short-term memory system as a whole, the control of action, and planning." (Gathercole & Baddeley, 1993) "..controlled by the central executive, which is capable of retrieving information from the store in the form of conscious awareness, of reflecting on that information and, where necessary, manipulating and modifying it." (Baddeley, 2010) "…integrating different types of information in working memory" (Prabhakaran, 2000) "The central executive is…implicated in alloca tion of attention resources…" (Tillman, Nyberg, Bohlin, 2008) "a single factor looms above the others in generality or pervasiveness. We presume that this central factor is responsible for influencing performance in a broad variety of cognitive and learning t asks. In the conventional abilities model, the central factor is reasoning ability, or general fluid intelligence *(Gy).* Reasoning ability is traditionally "considered to be at or near the core of what is *intelligence"* (Carroll, 1989, p. 56) (K yllonen and Christal, 1990)	**Intrapersonal.** -self-awareness -self-knowledge -self-management / judgment -management of feelings -metacognition -self-other people management

The Enhanced Working Memory (eWM) Model Matched to MI

Since the initial development of both the working memory construct and multiple intelligences theory, much research has been devoted to their exploration, elaboration, and implementation. Cognitive scientists have greatly detailed their models of human thinking while researchers into MI theory have focused on expanding its practical uses. These efforts have involved advances in cognitive modeling, neuroscience evidence, and creative practical applications. Table 3 presents a summary of various cognitive additions that elaborate on the basic WM model. Full details are available in Supplemental Information 4. Some new elements have been added and nuances to the basic three-part model have been described in more detail. The relationship among eWM, intelligence and real-world behaviors have also increased our appreciation for the interpretative limitations of WM test results.

Enhanced WM models have grown to include several immediate memory storage components including passive and active storage (Klingberg, 2006). The relationship between short and long-term memory is recognized as being complex, interactive, and not independent of content or meaning (Baddeley, et al., 2015). Various kinds of attention: alerting, orienting, selective, focused, etc. (Posner, 2016; Peterson and Posner, 2012; Duncan, 2001) are noted as being important influences on cognitive functioning beyond what basic WM tests assess. The predictive value of WM tests for IQ are less strong than originally assumed by researchers (Ackerman, et al., 2005).

Table 3. Enhanced working memory Model Summary

Extended Working Memory Model – Summary		
Component	**Sub-component**	**Multiple Intelligences Correlates**
Short-term Memory	Attention Alerting / Orienting WM Capacity	All the intelligences
Visuospatial	Passive Active storage Visual Spatial	Visual-spatial
Verbal	Oral Language Reading	Linguistic
Auditory	Immediate sound processing	Musical
Episodic Buffer	Multi-modal temporary storage	Kinesthetic Interpersonal Others
Central Executive	Executive processing Domain General Executive Sub-skills Working Self Attention and impulse control Self-regulation: cognitive & emotional Relational integration	Intrapersonal Logical-mathematical
WM & Real World performances	Academic skills School achievement Intelligence	Intrapersonal Interpersonal Logical-mathematical Linguistic

Note. Contemporary models of working memory are extended in ways that are closely matched with basic cognitive elements of several of the multiple intelligences.

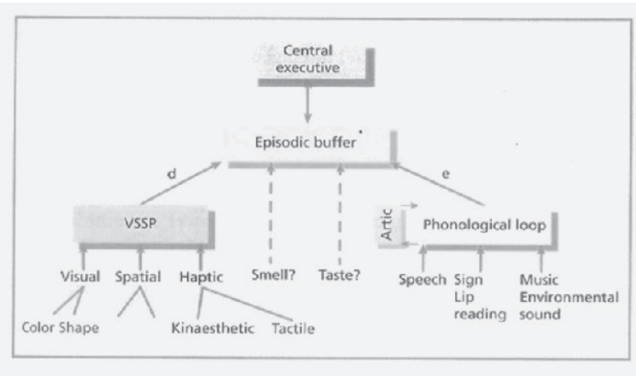
Multiple intelligences theory has advanced more in terms of its educational applications rather than its cognitive characteristics. These practical applications have emphasized how each intelligence can be leveraged to maximize success in both school and career development (Campbell and Campbell, 1999; Shearer, 2009; Shearer and Luzzo, 2009). Recent neuroscientific studies have identified core cognitive components for each intelligence that have their own unique neural frameworks (see Supplemental Information 3). Each of these core cognitive components has several levels of cognitive behavior from basic awareness to highly developed performances and productions.

Cognitive theories of visuospatial WM have been enhanced with the recognition of passive and active memorizing operations (Cowan, 2001; Repovs and Baddeley, 2006). A differentiation between visual and object immediate memory have also been detailed (Baker, et al., 1996; Repovs and Baddeley, 2006; Smith and Jonides, 1997). Multiple intelligences theory doesn't specify WM components for the visual-spatial intelligence but it explicitly differentiates among four different aspects of this intelligence: mental visualization, visual perception, working with objects, and spatial awareness. eWM emphasizes the mental components of visualization following the visual presentation of the testing stimuli. Obviously, manipulating objects or finding one's way through space are not involved in typical WM testing but some researchers have identified three-dimensional object representations as components of visuospatial WM (Smith and Jonides, 1997).

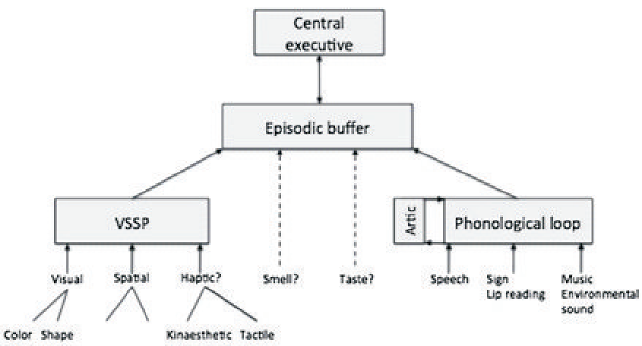
Verbal components of working memory have also been spilt into passive registration and the active rehearsal of the verbal content. Neuroscience evidence has helped to clarify a distinction between oral language and visual word processing. MI theory offers linguistic intelligence as the corollary to verbal WM. Linguistic intelligence has several core cognitive components where each has its own immediate memory and basic processing: mental inner speech, oral speech, reading, and writing. Baddeley refers to verbal WM processing as a "phonological loop" where the person repeats the test stimuli via mental rehearsal (Baddeley, 2012).

More recently the concept of an Episodic Buffer has been added to WM described by Reprovs & Baddeley (2006) as "… a multimodal store capable of integrating information into unitary episodic representations, termed episodic buffer…" (p. 15). This buffer uses multi-modal information to model the world and to solve problems (Baddeley, 2010). A more speculative model of eWM is presented by Baddeley (2012, 2015) in Figure 1. Note that it includes several previously unrecognized sense modalities such as haptic, smell, taste, and environmental sounds.

Figure 1. A speculative view of the flow of information from perception to working memory.
p. 83, Baddeley, A. Eysenck, M. and Anderson, M. (2015). Memory. London and New York: Psychology Press. and Baddeley, A. (2012). Working memory: Theories, models, and controversies. Annu.Rev. Psychol. 63:1-29.



(Below is an alternative black and white versions of the Baddeley chart that can be used in place of the color version. Dr. Baddeley has given his permission to reproduce this chart.)
Baddeley, A. Eysenck, M. & Anderson, M. (2015). Memory. London and New York: Psychology Press.



AR Baddeley A. 2012.
Annu. Rev. Psychol. 63:1–29

Several of the multiple intelligences in their basic forms are elements in Baddeley's Episodic Buffer and speculative model of eWM. Specifically, Baddeley has identified kinesthetic movement as part of either visuospatial or episodic immediate memory (Baddeley, 2000; Baddeley, et al., 2015). Awareness of music or sound are also easily associated with attention and immediate memory. Somers and colleagues (Michalka, et al., 2015, Noyce, et al., 2017 and Tobyne, et al., 2017) have identified two distinct auditory attentional control neural units in the lateral frontal cortex. These are part of "…specialized representations for timing and rhythm (that) exist in the frontal auditory-biased regions… transverse gyrus intersecting precentral sulcus (tgPCS) and caudal inferior frontal sulcus (cIFS)" (Michalka et al., 2015, p. 882).
It is less clear how the interpersonal or naturalist intelligences are associated with working memory, but they may be related indirectly to the Central Executive or other attentional control functions. Intrapersonal intelligence is most directly associated with the Central Executive but many of its functions have yet to be included in an extended working memory model. However, Conway (2000, 2005) has sketched a "working self" that is part of the Self-Memory System (SMS). The SMS has features very similar to intrapersonal intelligence described by Gardner except with a greater emphasis on levels of autobiographical memory. Conway's description of the cognitive functions of the "working self" provides a clear link between working memory and intrapersonal intelligence,
"… the goals of the working self form a subset of working-memory control processes organized into interconnected goal hierarchies that function to constrain cognition, and ultimately behavior, into effective ways of operating on the world" (2000, p. 265).

In the case of working memory, the "working self" is represented by the Central Executive in both conscious and non-conscious functions. For example, it has been noted by Gipps that the act of testing itself is a social interaction where the person's responses are influenced by social / cultural factors and long-term memories (Gipps, 1999; Jolles and Crone, 2012).
The biggest revisions to eWM have been insights into the components comprising the Central Executive that are assumed to be the neural mechanisms responsible for processing immediate sensory content (Sanchez-Cubillo, et al., 2009). Fundamental to the functioning of the Central Executive are various types of attention that have been elaborated by Posner, Peterson and others, as previously noted. These include alertness, divided, focused, sequential, switching, delayed, etc.
How exactly the Central Executive operates during working memory is a matter of some debate. Several different models for the executive processor have been proposed over the years. The most common is the idea of a single, central authority that guides the processing of the contents for memory (Baddeley, et al., 2015; Repovs and Baddeley, 2006) The Central Executive is also responsible for managing conflicts for divided attention (Peterson, et al., 1999) and emotional control (Beauregard, et al., 2001) and planning and monitoring (Smith and Jonides, 1999). There are also proposals for a dual or parallel processing executive system (Peterson, et al., 1999) that manages conflicting attentional inputs. Self-regulation cognitive and emotional are important duties of the executive when processing different forms of information (Posner, Rothbart, Tang, 2013; Posner, 2008). The effective performance of these subtle attentional processes may also draw on aspects of the logical-mathematical intelligence and the brain organizes complex information (Gardner, 1993a).
How the brain accomplishes these subtle, diverse, and complex tasks is yet to be determined but gradually our

understanding of the many roles of the frontal lobes are being revealed. One of the more interesting descriptions of the mystery of the prefrontal cortex is provided by John Duncan (2001) where he describes the subtle interaction between the person's subjective experience and the processing of information,

"Subjectively, a selective prefrontal focus on task-relevant information, with its accompanying dominant representation in sensory, motor, memory, motivational
and other systems, would correspond to the state of controlled, active attention to this information, or, equivalently, to controlled, active maintenance in working memory. In this way, the prefrontal cortex carries out a central function in configuring a flexible cognitive system to address specific, current concerns." (p. 825).

Duncan and Owen (2000) also describe the ability of frontal lobe neurons to change their function this way, "… a specific network of prefrontal regions recruited to solve diverse cognitive problems … the same specific regions of the frontal lobe are activated by different forms of cognitive demand" (p. 480). Gardner (1993a) describes a capacity of the intrapersonal intelligence that is aligned with Duncan's understanding of the frontal lobes' ability to manage diverse forms of content "…the personal intelligences conform to our working notions of basic intelligence. Yet it is undoubtedly true that the diverse forms that the personal intelligences can eventually assume are among their most outstanding features" (p. 275).

The concept of intrapersonal intelligence is a unique contribution of MI theory to the literature on intelligence. Defining the self as a coherent set of abilities rather than as a psycho-social or personality characteristic was a radical idea in 1983. Of course, defining the self is subject to an endless variety of interpretations so describing it as an "intelligence" is challenging. Gardner's original description emphasized the balance between self and other in society and how this balance is managed by different cultures (1993a). The definition of intrapersonal intelligence has evolved with a greater appreciation for cognitive and metacognitive skills along with its psychosocial / affective dimensions.

As noted above Conway's description of the "working self" provides a clear connection between fundamental aspects of intrapersonal intelligence (specifically "event-specific knowledge") and a person's cognitive processes during working memory task performance. These theoretical linkages have yet to be confirmed but their neural features are described below.

One of the nuances of working memory added by researchers in recent years pertains to the role of the Central Executive as a binder or integrator of sensory input (Baddeley, 2015; Oberauer, et al. 2008). While it is an evolving concept, it blurs the line separating short and long-term memory. It also expands the role of the executive from merely an information manager to more of a maker of meaning within a cultural context. It was originally assumed that working memory was just a basic, data processing mechanism not involving long-term memory or meaning.

This recognition that even simple cognitive contents (numbers, shapes, words) can have cultural meaning to the person that impacts cognitive skill performance was described by Gardner in 1993,

"…intelligences cannot be viewed merely as a group of raw computational capacities. The world is enwrapped in meanings, and intelligences can be implemented only to the extent that they partake of these meanings, that they enable the individual to develop into a functioning, symbol-using member of his community…there may be "dumb" capacities at the center of intelligence; but it is equally true that these capacities must be made "smarter" if one is successfully to interact with the surrounding society."
(p. 297)

It is of interest to the present investigation that executive-attention control has been identified as the mechanism that links WM with intelligence (Conway, et al., 2003; Duncan, et al., 2000). There are many logical links between WM and the multiple intelligences but are these theoretically aligned concepts supported by neuroscience evidence? Part 2 provides a summary of a review of a multitude of neuroscientific examinations of many human abilities.

Part 2

Neural Correspondences Between Working Memory and Multiple Intelligences

Mapping of the neural activity during WM tasks to specific psychological terms
is still a work in progress (Klingberg, 2010, p. 318)

For more than two decades neural imaging techniques such as PET and fMRI scans have been used to better understand how various brain regions process working memory, intelligence, and a wide variety of cognitive abilities. These technologies have provided valuable information as complements to behavioral data to test and revise our theoretical models of cognitive behavior. This investigation is the sixth in a multi-part study that examined numerous neural studies of working memory and compared those results to a review of over 500 studies of the neural basis for each of the multiple intelligences (Shearer and Karanian, 2017). A description of the data collection procedures is available in Supplemental Information 2 and neural organization framework in Supplemental Information 5 and database sample in Supplemental 7.

Part One of this report compared the theoretical models of working memory to the multiple intelligences and revealed areas of agreement and differences. Part Two compares and contrasts their neural bases to assess the degree of their relatedness. Primary neural regions and sub-regions are compared in Tables 4 through 8. These values represent the number of times that specific neural regions are cited in the literature as corresponding to the designated cognitive component.

Working memory (WM) and General Intelligence (g)

Working memory has often been cited a good predictor for a person's general intelligence (Kyllonen and Christal, 1990; Tillman, Nyberg and Bohlin, 2008; Conway, Kane and Engle, 2003). working memory tests include briefer versions of tasks often included in the measurement of IQ or g, including verbal skill, visual-spatial abilities, and attentional regulation.

Table 4 displays the results of the neural literature analysis of WM and g. Neural bases for g were described by Shearer and Karanian (2017). Additional information is provided in Supplemental Information 6. There is a high rate of agreement for both primary and sub-regions cited. Frontal and parietal are both in the top two places but with frontal cited much more frequently for WM than for g (52% vs. 33%). The number of citations for the cingulate cortex is tied. The other noteworthy difference is that temporal is more strongly cited for g than it is for WM (15% vs. 5%).

Sub-region comparisons are remarkably similar with all five of the g sub-regions included in the list of WM sub-regions. Only the dl PFC and premotor are cited for WM and not for g.

Table 4. Working Memory and General Intelligence Neural Regions Comparisons

	Working memory and General Intelligence Neural Regions Comparisons			
	Primary Regions (%)		Sub-regions (ct)	
	Working memory	General Intelligence	Working memory	General Intelligence
Rank 1	Frontal (53)	Frontal (33) Parietal (33)	PFC (36)	Inferior Parietal Lobe (13)
2	Parietal (21)	Temporal (15)	dl PFC (19)	PFC (12)
3	Cingulate (12)	Cingulate (12)	Premotor (16) ACC (16)	ACC (5)
4	Temporal (5)		Inferior Parietal Lobe (14)	Inferior Frontal Gyrus (7)
5			Inferior Frontal Gyrus (10) Supramarginal Gyrus (10)	Supramarginal Gyrus (5)

Note. Total citations: working memory: Primary-149; Sub-regions-233. General Intelligence: Primary-100; Sub-regions- 122. Abbreviations: PFC = Prefrontal Cortex; ACC= Anterior Cingulate Cortex.

Executive WM Component and Intrapersonal Intelligence

Executive functions are the WM components responsible for the mental processing of stimuli held in immediate memory. This is the "working" aspect of immediate memory and is often associated with attention, impulse control, and self-regulation. A core function of intrapersonal intelligence is the management of one's self including behaviors, affects, and cognitions.

In Table 5 we see a high rate of agreement between the primary neural regions cited for the Executive WM and intrapersonal intelligence. Frontal and cingulate cortices are highest for both constructs and at comparable citation rates. Temporal and subcortical citations are also nearly equal. There is some discrepancy between temporal citations where (once again) there are fewer citations for WM than for the intrapersonal intelligence (6 vs. 16, respectively).

Four of five sub-regions are the same for both Executive WM and intrapersonal. Intrapersonal includes two additional PFC sub-regions as compared to an additional cingulate sub-region cited for Executive WM.

Table 5. Executive WM and Intrapersonal Neural Regions Comparisons

	Executive WM and Intrapersonal Neural Regions Comparisons			
	Primary Regions (%)		Sub-regions (ct)	
	Executive WM	Intrapersonal	Executive WM)	Intrapersonal
Rank 1	Frontal (48)	Frontal (41)	PFC (19)	PFC (73)
2	Cingulate (25)	Cingulate (17)	ACC (14)	ACC (27)
3	Parietal (13)	Temporal (16)	dACC (8)	dmPFC (18)
4	Temporal (6)	Parietal (11)	dPFC (7)	lPFC (15) vmPFC (13)
5	Subcortical (5)	Subcortical (9)	Basal Ganglia (2)	Basal Ganglia (10)

Note. Total citations: Executive WM: Primary-149; Sub-regions-233. Intrapersonal: Primary-219; Sub-regions-437. Abbreviations: PFC= Prefrontal Cortex; ACC = Anterior Cingulate Cortex; dACC= Dorsal Angerior Cingulate Cortex; dPFC= Dorsal Prefrontal Cortex; dmPFC= Dorsal Medial Prefrontal Cortex; vmPFC= Ventral Medial Prefrontal Cortex.

Verbal WM Compared with Linguistic Intelligence

Immediate verbal memory is a core component of WM and can be tested with either oral or written text. Linguistic intelligence also includes oral, written, or inner speech.

There are some discrepancies in the rates and arrangements of the primary neural regions cited for Verbal WM and linguistic intelligence. Temporal is highest for linguistic intelligence (40%) and missing entirely from the Verbal WM list. Frontal (57% vs. 27%) and parietal (30% vs. 12%) are cited at much higher levels for Verbal WM as compared to linguistic. The two constructs share two sub-regions Inferior Frontal Gyrus and Inferior Parietal Lobule while there are three other sub-regions that are different. See Table 6.

Table 6. Verbal WM and Linguistic Neural Regions Comparisons

	Verbal WM and Linguistic Neural Regions Comparisons			
	Primary Regions (%)		Sub-regions (ct)	
	Verbal WM	Linguistic	Verbal WM	Linguistic
Rank 1	Frontal (57)	Temporal (40)	Inferior Parietal Lobe (5) Premotor (5) Inferior Frontal Gyrus (5	Superior Temporal Gyrus (15)
2	Parietal (30)	Frontal (27)		Inferior Frontal Gyrus (14)
3	Insular (4) Cingulate (4) Cerebellum (4)	Parietal (12)		Broca's Area (13)
4		Occipital (7)		Inferior Parietal Lobule (10)

Note. Total citations: Verbal WM: Primary-23; Sub-regions-39. Linguistic: Primary-124; Sub-regions-238.

Visual Working Memory (VWM) and Visual-spatial Intelligence

Visual tasks are included as an essential component of all working memory tests. This includes visual input and / or objects that are memorized and sometimes mentally manipulated. Visual-spatial intelligence includes both mental imagery as well as the physical manipulation of objects or spatial arrangements.

Table 7 reveals that the neural components for VWM and visual-spatial intelligence are quite similar with some notable differences. The top two primary regions are the same for both constructs, frontal, and parietal, with VWM have higher values for both regions. Citations for occipital are nearly identical while the number of temporal citations are different (2% for VWM and 16% for visual-spatial).

There are three sub-regions shared by both VWM and visual-spatial motor, premotor and PFC and three sub-regions that are different. Of interest, visual-spatial intelligence includes an additional temporal sub-region while VWM includes two parietal sub-regions.

Table 7. Visual WM and Visual-spatial Neural Regions Comparisons

	Visual WM and Visual-spatial Neural Regions Comparisons			
	Primary Regions (%)		Sub-regions (ct)	
Rank	Visual WM	Visual-spatial	Visual WM	Visual-spatial
1	Frontal (56)	Frontal (39)	PFC (11)	Motor Cortex (21)
2	Parietal (31)	Parietal (20)	Premotor (7)	PFC (17)
3	Occipital (11)	Temporal (16)	Inferior Parietal Lobe (6)	Premotor (12)
4	Temporal (2)	Occipital (10)	Posterior Parietal Lobe (5)	Medial Temporal Lobe (8)
5			Motor Cortex (4)	

Note. Total citations: Visual WM: Primary-45; Sub-regions-69. Visual-spatial: Primary-143; Sub-regions-308. PFC= Prefrontal Cortex.

Auditory Working Memory Compared with Musical Intelligence

Attending to and processing sounds are tasks not included in the typical WM testing but have recently been noted as an important component along with visual and phonological processing. There is limited neuroscientific data regarding auditory WM so the comparisons below are tentative. Both frontal and temporal are the highest primary regions for both constructs. Due to the limited number of citations the percentages cannot be confidently interpreted but the order is instructive. The same is true for the interpretation of additional primary regions beyond the top two which are appropriate.

There are two sub-regions in common but five that are unique. These two sub-regions superior temporal gyrus and motor are noted as essential neural processors for auditory information.

Table 8. Auditory WM and Musical Intelligence Neural Regions Comparisons

	Auditory WM and Musical Neural Regions Comparisons			
	Primary Regions (%)		Sub-regions (ct)	
Rank	Auditory WM	Musical	Auditory WM	Musical
1	Frontal (57)	Frontal (41)	Precentral Gyrus (4)	Motor (31)
2	Temporal (43)	Temporal (27)	Superior Temporal Gyrus (2) Motor Cortex (2) Inferior Frontal Gyrus (2) Transverse Gyrus (2)	Superior Temporal Gyrus (23)
3		Subcortical (16)		Primary Auditory Cortex (19)
4		Cerebellum (10)		Premotor (12)

Note. Total citations: Auditory WM: Primary-7; Sub-regions-21. Musical: Primary-103;
Sub-regions-187.

Summary

There are a large number of neural regions cited in common between WM, general intelligence, and matched multiple intelligences. These are not perfectly aligned, however. There are also neural distinctions that highlight the differences between the cognitive basics of working memory and an intelligence with a wider array of cognitive components.

Of particular note, the temporal cortex is cited more often for the intelligences than for WM while the frontal cortex is more dominant for working memory. The neural relationships between WM / g and Executive WM / intrapersonal intelligence are remarkably similar in their configurations. Visual WM and visual-spatial intelligence are also well aligned in their neural composition. The neural differences between Verbal WM and linguistic intelligence are surprising. The reasons for this discrepancy are unclear but it might be due to the distinct split between oral speech and reading text that use different sensory inputs. Auditory WM and musical intelligence have neural regions in common that focus on the processing of sound but there is too little data to have great confidence in these findings.

Overall, there is a remarkable congruence between the neural architectures for working memory and its components matched with several multiple intelligences and general intelligence. This finding reinforces the theoretical alignments between an extended model of WM matched with several of the multiple intelligences described in Part One. These findings support Klingberg's statement that our understanding of the cognitive skills linked to neural architectures is still evolving. These coherent neural findings suggest that our model of WM can be enhanced with the inclusion of the multiple intelligences for a broader understanding of an individual's working memory capacities both in and outside of school.

Part 3

Implications for Cognitive Training and Education (CTE)

Future research should not investigate whether brain training works but rather, it should continue to determine factors that moderate transfer and investigate how these factors can be manipulated to make training most effective (Jaeggi, et al., 2011, p. 10085)

The evolution of the field of cognitive training and educational activities has mirrored advancements in working memory theory. Cognitive training and remediation activities began with paper-and-pencil tasks that emphasized logical reasoning puzzles. As computers and software evolved, these activities were transformed into basic problem-solving tasks, cartoons, and simple games played on the screen. These simplistic software-based tasks underwent a drastic evolution as computers became more powerful and prevalent and software greatly increased in realism and sophistication. To the point where the title of recent article in a computer magazine asked a question important to an aging population, "Could a Video Game Strengthen Your Aging Brain?" (Vlasits, 2017).

Of course, enhancing cognitive functioning is of importance to people of all ages. Teachers, tutors, and school psychologists have deep concerns about how to help children in the classroom. Parents are charged with guiding their children through the school experience as well as finding a successful path into adulthood. Deficits in working memory are associated with a host of problems including Attention Deficit Hyperactivity Disorder (Rogers, et. al, 2011), Learning Disabilities (Swanson, et al, 1993), reading difficulties (Danman, 1980; Gathercole and Baddeley, 1993), math impairments (McLean and Hitch, 1999; DeStefano and LeFevre, 2004), classroom behaviors (Alloway, et al, 2009), psychiatric orders (Glahn, et al. 2005), post-traumatic stress disorder (Honzel, Justus and Swick, 2014).), and aging (De Beni and Palladino, 2004).

A review of the literature on the efficacy of cognitive training and education is beyond the scope of this report but the conclusion reached by most reviewers is that the results are decidedly mixed. Some programs are effective at obtaining specific results while others are of marginal effectiveness (Melby-Lervag and Hulme, 2012; Baddeley, et al., 2015; Shah, et al., 2017; Jolles and Crone, 2012; Shipstead, Hicks and Engle, 2012; Klingberg, 2010). Sorting out the effective from ineffective programs can be difficult because there are a wide variety of approaches with varying target goals, age ranges, and evaluation criteria.

The most common criticism of lab-based working memory training is voiced by Baddeley et al., (2015) ". . .there is good evidence for an effect of training, with generalization to other WM tasks, but little evidence that it automatically generalizes to real-world environments . . . evidence for the practical transfer to scholastic topics such as reading and arithmetic is at present extremely weak" (p. 92). This conclusion echoes that of Arthur Jensen who commented that we have techniques for improving specific skills, but these do not generalize to developing a person's intelligence (cited by Colom, et al, 2005; Jensen, 1998).

Some researchers believe that CTE is most effective when it targets Central Executive skills. This is illustrated by Posner, Rothbart and Tang (2013) who report executive attention training achieved three objectives: strengthening neural networks, near transfer to other test results, and far transfer to daily behavior and intelligence scores. However, Gathercole et al., (2012) question the efficiency of brain training to " . . .reflect quantitative improvements in the efficiency of the neural substrate . . ." and instead " . . . training gains . . . arise from the development of relatively task-specific strategies that trainees fail to apply spontaneously to everyday activities that tax working memory" (p. 202).

The desire to improve the transfer of working memory skills from the training lab to real life contexts has led researchers down two paths described by Posner, Rothbart and Tang (2013). They identify CTE programs in terms of two main types, "network training" and "brain state training" with each having advantages and disadvantages.

Software that is enriched, engaging and aimed at enhancing specific cognitive skills is a contemporary example of "network training". "Brain state training" activities promote a state of mind that is conducive to improved WM rather exercising that skill directly. Learning meditation and mindfulness to enhance self-regulation are prime examples.

A third strategy to facilitate transfer is the active creation of cognitive behavioral connections between the lab and the real-world as suggested by Baddeley, et al., "Generalization can occur but it needs the therapist or trainer to build a bridge between the clinic and the world outside" (2015, p. 92).

Could this be one of the "bridges" that Bruer was referring to when he described the gap between our knowledge of the brain and appropriate educational strategies? We will now explore how the theory of multiple intelligences provides a broad and over-arching theoretical bridge between neuroscience evidence and effective CTE.

Multiple Intelligences Bridges to Transfer of Learning

MI theory has inspired educators around the world to design instruction and alter curriculum to promote transfer between the classroom and the real world. Gardner led this movement (Gardner, 1993b) with his advice that MI theory should be implemented with two goals in mind: 1) design instruction that is modeled after the knowledge and skills as practiced by professionals; and 2) students spend more time outside the classroom in activities such as apprenticeships and "job shadowing" to gain a deeper understanding how academic knowledge is utilized in the field. In these cases, teachers act as both discipline experts as well as "coaches" who facilitate skills / knowledge transfer.

The three approaches to CTE transfer described above by Posner and Baddeley are related to educational strategies advocated by Perkins and Salomon (1988) to increase the transferability of knowledge and skills. It has long been argued that academic knowledge is too often "inert" or "contextually welded" so that students do not carry over what is learned into new contexts. Two types of transfer low road and high road -- are describe by Perkins and Salomon (1988) in this way, *Low road transfer reflects the automatic triggering of well-practiced routines in circumstances where there is considerable perceptual similarity to the original learning context . . . high road transfer depends on deliberate mindful abstraction of skill or knowledge from one context for application in another . . . (p. 25) (italics added)*

These two types of transfer echo Gardner's objectives for the use of the multiple intelligences in schools. The third strategy to facilitate transfer is called "bridging" which involves ". . . teaching so as to meet better the conditions for high road transfer. Rather than expecting students to achieve transfer spontaneously one "mediates" the needed process of abstraction and connection making" (Perkins and Salomon, 1988, p. 28). In their review of the effectiveness of cognitive retraining software, Gathercole, Dunning and Holmes (2012) conclude that computerized cognitive training programs need to explicitly provide trainees with practice in transferring new skills to the everyday classroom (if the goal is to develop academic skills). In order to achieve cognitive transfer in the lab, Gathercole, Dunning and Holmes (2012) are, ". . . developing a complex task environment designed to bridge the gap between the highly structured and artificial activities (of the lab) . . . for flexible use (by students) in educational settings" (p. 202).

Gardner has cited the importance of "personalizing" instruction if it is to be maximally engaging, motivating, and effective (1993b, 1999). This is qualitatively different from "individualization" which is usually interpreted from an IQ or working memory capacity perspective where individuals are ranked from high to low along a single dimension. This results in a restricted number of options for altering instruction limited to the linguistic and logical-mathematical intelligences. For example, "Because of limited WM capacity the student should be provided with simple one-step verbal instructions." While this may helpful advice, it is limited in its ultimate effectiveness because it overlooks the student's intellectual strengths and motivation to apply alternative learning strategies in everyday life. For example, "Because of your keen musical ability let's see if we can translate the steps for multiplying fractions into a familiar jingle or rhyme."

Another example pertains to how the oft neglected naturalist intelligence relates to working memory and attention. Children with ADHD display highly distracted behaviors while in the classroom setting but become appropriately focused and on-task during an environmental studies activity in the field or woods (Nature Therapy and ADHD, 2017).

Merging Neural Cognitive Training with MI-Inspired Activities

". . . we do not rule out the possibility that WM training could be made effective. . .
while there is logic to WM training (increase WM and improve related abilities),
this literature is still struggling to find a theory." (Shipstead et al., 2012, p.191)

As the field of brain training has evolved from the simple to the sophisticated we see parallels with advancements in WM theory from a few basic components to an enriched and nuanced understanding of how the mind / brain processes knowledge and skills. Both CTE and MI-inspired education share the goal of promoting the transfer of learning from the classroom / lab to students' effective thinking in everyday life (Hoerr, 1994). Perkins and Solomon (1988) write that educators are familiar with strategies that facilitate transfer but that they are not implemented systematically so they "saturate the context of education with attention to transfer" (p. 29). Such saturation and systematic use of metacognitive strategies and a variety of cognitive abilities serve to promote cognitive/emotional engagement so as to promote "deep learning". Deep learning (Baddeley, et al, 2015; Craik and Tulving, 1975) implies a lasting change in neural activation patterns so that "bridging" between the lab and everyday problem-solving results in high level performances.

A few examples of advanced neural cognitive training programs that embody the MI-inspired philosophy will illustrate how these approaches strive to promote transfer by using direct, in-direct, and facilitated transfer strategies.

Cognitive training video games demonstrate how training activities can benefit from the multi-media programs developed by the entertainment industry (Green and Bavelier, 2015; Anguera and Gazzaley, 2015). What is noteworthy about these video game-type exercises is how enriched they are with multi-sensory stimuli aligned with the multiple intelligences:

Many of today's most popular video games involve high levels of art, captivating music, and intricate storylines to create immersive environments for an enhanced player experience . . . (Anguera and Gazzaley, 2015, p. 160).

Rather than doing brain training in an artificial lab context, Mackey, et al (2017) tested a classroom-based cognitive training program that " . . .can be tailored to a student's performance level to keep the student engaged but not frustrated. . . involve (ing) multiple cognitive domains (e.g., visuospatial, semantic, and numerical) in order to maximize breadth of transfer" (p. 86). These games also involve dynamic social interaction and teacher involvement. The results of their pilot project were mixed. Overall, the treatment group did not out-perform the control group on academic tests. However, the sub-group that improved the most on the cognitive training tasks also raised their math performance more than their peers. This outcome suggests transfer of learning by the students who are most in need of cognitive skills training but not the typical student.

Based on the students' and teachers' responses to their classroom-based program, Mackey, et al. make suggestions for CTE that are aligned with an MI-inspired strengths-based personalized instruction. Cognitive training should ". . .include as key features …social interaction with peers and instructors, individualized difficulty progression, varied tasks and domains, (and) emphasis on metacognition" (p. 93,). These suggestions make use of the intrapersonal and interpersonal intelligences as well as personalizing the activities to engage a student's interests and abilities. Greater instructor involvement also lends itself to guiding students to transfer skills developed during CTE to academic subjects.

Computer and video-game based approaches to cognitive training become ever more sophisticated in their modeling of everyday life, engaging multiple intelligences, and personalizing their interactions with respondents. These “brain training” programs show great promise. Meanwhile, other researchers take a “brain state training” approach that broadens the range of intelligences activated beyond what software can emulate. These innovative approaches to improving working memory highlight the importance of a particular intelligence to engage and motivate trainees to maximize the benefit of their unique MI ability. Such strategies embody a personalized “strengths vs. deficits” approach that is at the heart of the MI educational philosophy (Chen, Moran and Gardner, 1998; Kornhaber, et al, 2004; Campbell & Campbell, 1999). See Table 9.

Because many of these innovative programs are in their early stages of development their research bases are still slim. However, they represent creative approaches to long-standing problems in cognitive training and education. They are each building blocks in that bridge between our knowledge of the brain and the host of educational and cognitive problems that John Bruer described as “a bridge too far” for the emerging field of educational cognitive neuroscience.

Table 9. Cognitive Training and Research Programs Using Specific Multiple Intelligences

Cognitive Training and Research Programs Using Specific Multiple Intelligences

Multiple Intelligences	WM Component	Program	Activity	Authors
Intrapersonal	Central Executive	Integrative Body-Mind Training	Meditation and mindfulness	Tang,et al. 2008 Tang, et al. 2012
Interpersonal	Speed of processing, Executive WM	Discussion of social issue	Social interaction	Ybarra, et al.,2008
Kinesthetic	All cognitive domains esp. central executive	Physical activity	Moderate intensity physical activity	Erickson, Hillman & Kramer, 2015
Musical	Central executive	Musical training	Retrieving and monitoring information: anticipation of sequences	Vandervet, 2015 Pallesen, et al. 2010 Hsu, 2017
Logical-mathematical / intrapersonal	Fluid intelligence	Dual n-back task	Identify when stimuli matches presented previously	Jaeggi, et al., 2008
Visual-spatial	Visuospatial			Peretz, 2011 Klingberg, 2006 Toril, et al. 2016
Naturalist	Mindfulness / IFG / WM	Animal interaction	Touching or stroking a dog	Gee, et al., 2015 Kobayashi, 2017 Gee, et al. 2014 Henry, 2015

Note. Summaries of exemplar programs that focus on one of the multiple intelligences are provided in Supplemental Information 8. Also included are several research reports that examine the neural relationship between the various intelligences and working memory. These are provided to illustrate and inspire researchers and practitioners to continue to explore these relationships.

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Supplemental Information

Working Memory -- Building Blocks of Intelligence or an Incomplete Framework?

Towards a Model of Enhanced Working Memory Informed by Multiple Intelligences Theory

1. Multiple Intelligences Definitions and Sample Corresponding Careers
2. MI Neuroscience Investigation Data Collection and Analyses
3. Neural Regions Associated with Cognitive Units for the Multiple Intelligences
4. Components of Extended Working Memory Matched with Multiple Intelligences
5. Neural Organization Framework
6. Neural Correlates of Working Memory Capacity and Matched Multiple Intelligences
7. WM Neural Database Sample
8. Summaries of Programs and Research that Focus on the Relationship between Multiple Intelligences and Working Memory
9. Neuroscientific Evidence Supporting the Validity of MI Theory - Summary

Supplemental Information 1. Multiple Intelligences Definitions and Sample Corresponding Careers

Intelligence	Brief Description	Sample Careers
Musical	To think in sounds, rhythms, melodies and rhymes. To be sensitive to pitch, rhythm, timbre and tone. To recognize, create and reproduce music by using an instrument or voice. To engage in active listening and ide ntify connections between music and emotions.	Choir director Instrumentalist Music teacher Song writer
Kinesthetic	To think in movements and to use the body in skilled and complicated ways for expressive and goal directed activities. A sense of timing, coordination for whole body movement and the use of hands for manipulating objects.	Athlete Choreographer Dancer Equestrian
Logical-Mathematical	To think of cause and effect connections and to understand relationships among actions, objects or ideas. T o calculate, quantify or consider propositions and perform complex mathematical or logical operations. Involves inductive and deductive reasoning skills as well as critical and creative problem solving	Accountant Bookkeeper Electrical engineer Systems analyst
Spatial	To think in pictures and to perceive the visual world accurately. To think in three -dimensions and to transform one's perceptions and re -create aspects of one's visual experience via imagination. To work with objects effectively.	Architect Craftsperson Interior designer Landscape architect
Linguistic	To think in words and to use language to express and understand complex meanings. Sensitivity to the meaning of words and the order among words, sounds, rhythms, inflections. To reflect on th e use of language in everyday life.	Attorney Journalist Poet Public relations director
Interpersonal	To think about and understand another person. To have empathy and recognize distinctions among people and to appreciate their perspectives with sensitivity to their motives, moods and intentions. Involves interacting effectively with one or more people in familiar, casual or working circumstances.	Counselor Nurse Salesperson Teacher
Intrapersonal	To think about and understand one's self. To be aware of one's strengths and weaknesses and to plan effectively to achieve personal goals. Reflecting on and monitoring one's thoughts and feelings and regulating them effectively. Ability to monitor one's self in interpersonal relationships and to act with personal efficacy.	Clergy Monk Police officer Psychologist
Naturalist	To understand the natural world including plants, animals and scientific studies. To recognize, name and classify individuals, species and ecological relationships. To interact effectively with living creatures and discern patterns of life and natural forces.	Biologist Farmer Meteorologist Veterinarian

Supplemental Information 2. Neuroscientific Evidence Data Collection Procedures

A Systematic, Multi-methods Review of the Neuroscientific Literature

This investigation began with a detailed review of the various cognitive units and specific skills associated with g and the eight intelligences. For example, musical intelligence describes operationally skills such as instrumental innovation, vocal musicality, compositional innovation, and aesthetic and critical appreciation. The ability sets for each of the eight intelligences includes logical skill (g) as well as creative performance (e.g., musical notation and jazz improvisation) so the review of musical neuroscience studies would ideally be inclusive of this range of abilities. Charts were constructed for the eight intelligences with rows for MI Cognitive Units and columns for matched Neural Structures and Cognitive Skills.

Using the terms related to each Cognitive Unit or Specific Skill, PubMed and Google Scholar were used to search for published peer reviewed empirical neuroscience studies. The goal was to identify a minimum of three to five studies per major skill area. Studies of personality characteristics or dispositions were not included (e.g., introversion, diligence, etc.). Theoretical articles or books were used mainly for background information. Several extensive meta-analysis and topic reviews served as guides to finding pertinent studies in the target area.

Excerpts from experiments that describe neural structures underpinning carefully defined cognitive skills were entered into charts per Cognitive Unit. The next step was to review the data charts and harmonize the various neural descriptors according to standard neural anatomical terminology. These lists were then organized according to eight main brain regions, four levels of sub-regions, and multi-regions. Primary regions were defined as frontal, temporal, parietal, occipital, subcortical, cingulate, cerebellum, and insular. Citations for each category were then tallied. Frontal cortex was the most frequently cited primary region, so it was deemed necessary to determine if the eight intelligences activated it differentially.

MI Neuroscience Investigation Data Collection and Analyses

Steps in the process of investigating the neural bases for the multiple intelligences.

Step 1. Identify Core Cognitive Components for each Intelligence

Review definitions and descriptions by Gardner in Frames of Mind. Review Spectrum assessment system for behavioral aspects of each intelligence.

Step 2. Intelligence Charts 5 columns descriptive definition

Column 1 = core cognitive component.
Column 2 = neural regions direct quotes
Column 3= descriptions of cognitive functions matched to neural processes - direct quotes
Column 4= citation source Column 5 = additional MI overlap

Step 3. Data Sources: Review articles and primary data studies.

Find neuroscience studies matched to intelligence core cognitive components (CCC) and skills. Search Google Scholar and PubMed. Identify review articles and primary sources. Gather 3 10 studies per component. Include only peer reviewed articles from authoritative journals with quantitative analyses. Align cognitive neural processes with MI core components. Enter direct quotations from studies in Chart columns. Adjust CCC to better align with neuroscience evidence.

Step 4. SPSS database

Per Core Cognitive Component: enter neural regions into database according to Neural Organization Framework: (variables) Primary Regions, Sub-Regions (levels 1 4), Multi-Regions. Positive and Negative activations.

Step 5. Determine Dominant Neural Regions per Intelligence and General Intelligence.

- Rank Order Primary, Sub-Regions and Multi-Regions Per Intelligence
- Calculate percentages per region for comparisons
- Compare General Intelligence neural architecture to each MI

Step 6. List Particular Frontal Neural Structures

- Compare intelligences and components

Step 7. Summarize Dominant Neural Regions (Primary to Sub-Region 3)

- Per intelligence

Step 8. Determine Dominant Neural Regions per Core Cognitive Components

- Rank Order Primary, Sub-Regions and Multi-Regions Per Component
- Summarize dominant neural regions (primary - sub-region 3) per component

Step 9. Cognitive Skill Units Analyses

- Venn diagram neural regions in common and unique to Skill Units

Supplemental Information 3. Neural Regions Associated with Cognitive Units for the Multiple Intelligences

Intrapersonal Unit Comparisons for Primary Regions

Intrapersonal: Primary Region Unit Comparisons								
Self-Awareness			**Self-Regulation**			**Executive Functions**		
Regions	ct	%	Regions	ct	%	Regions	ct	%
Frontal Cortex	**65**	**37.6**	**Frontal Cortex**	**14**	**30.4**	**Frontal Cortex**	**11**	**50.0**
Temporal Cortex	*32*	*18.5*	**Temporal Cortex**	**10**	**21.7**	Parietal Cortex	3	13.6
Cingulate Cortex	*29*	*16.8*	*Cingulate Cortex*	*8*	*17.4*	Subcortical	3	13.6
Parietal Cortex	*20*	*11.6*	*Parietal Cortex*	*7*	*15.2*	Cingulate Cortex	3	13.6
Subcortical	*15*	*8.7*	Subcortical	4	8.7	Insular Cortex	2	9.1
Insular Cortex	*10*	*5.8*	Insular Cortex	3	6.5			
Cerebellum	2	1.2						
Total	173	100	Total	46	100	Total	22	100

*8 Primary Neural Regions. **Bold** = Top tier; *Ital* = 2nd tier; Plain text = Bottom tier.

Interpersonal: Primary Regions Skill Unit Comparisons

Interpersonal: Primary Region Skill Unit Comparisons								
Understanding			Leadership			Social Perception		
Regions	ct	%	Regions	ct	%	Regions	ct	%
Frontal Cortex	**17**	**68.0**	**Frontal Cortex**	**8**	**30.8**	**Temporal Cortex**	**14**	**45.2**
Cingulate Cortex	*5*	*20.0*	**Temporal Cortex**	**8**	**30.8**	*Parietal Cortex*	*4*	*12.9*
Temporal Cortex	2	8.0	*Cingulate Cortex*	*4*	*15.4*	*Frontal Cortex*	*4*	*12.9*
Parietal Cortex	1	4.0	*Parietal Cortex*	*3*	*11.5*	*Subcortical*	*4*	*12.9*
			Occipital Cortex	1	3.8	Insular Cortex	2	6.5
			Subcortical	1	3.8	Cingulate Cortex	2	6.5
			Insular Cortex	1	3.8	Occipital Cortex	1	3.2
Total	26	100		29	100		39	100

*8 Primary Neural Regions. **Bold** = Top tier; *Ital* = 2nd tier; Plain text = Bottom tier

Linguistic: Primary Regions Skill Unit Comparisons

Linguistic: Primary Regions Skill Unit Comparisons								
Speech			**Reading**			**Writing**		
Regions	ct	%	Regions	ct	%	Regions	ct	%
Temporal Cortex	**12**	**52.2**	**Temporal Cortex**	**13**	**34.2**	**Frontal Cortex**	**13**	**31.0**
Frontal Cortex	*5*	*21.7*	**Frontal Cortex**	**11**	**28.9**	**Occipital Cortex**	**8**	**19.0**
Parietal Cortex	*4*	*17.4*	**Parietal Cortex**	**8**	**21.1**	*Subcortical*	*5*	*11.9*
Cingulate Cortex	1	4.3	Occipital Cortex	2	5.3	*Temporal Cortex*	*5*	*11.9*
Cerebellum	1	4.3	Cingulate Cortex	2	5.3	*Parietal Cortex*	*4*	*9.5*
			Subcortical	2	5.3	Cingulate Cortex	3	7.1
						Insular Cortex	2	4.8
						Cerebellum	2	4.8
Total	23	100	Total	38	100	Total	42	100

*8 Primary Neural Regions. **Bold** = Top tier; *Ital* = 2nd tier; plain text = Bottom tier.

Logical-mathematical Unit Comparisons for Primary Regions

Logical-mathematical: Primary Region Unit Comparisons								
Logical Reasoning			**Mathematical Reasoning**			***G***		
Regions	ct	%	Regions	ct	%	Regions	ct	%
Temporal Cortex	**15**	**37.5**	**Parietal Cortex**	**18**	**51.4**	**Parietal Cortex**	**8**	**33.0**
Frontal Cortex	**13**	**32.5**	**Frontal Cortex**	**11**	**31.4**	**Frontal Cortex**	**8**	**33.0**
Parietal Cortex	*6*	*15.0*	*Cingulate Cortex*	*4*	*11.4*	Subcortical	3	12.5
Cingulate Cortex	*3*	*7.5*	Cerebellum	1	2.9	Temporal Cortex	3	12.5
Occipital Cortex	1	2.5	Temporal Cortex	1	2.9	Occipital Cortex	2	8.3
Insular Cortex	1	2.5						
Subcortical	1	2.5						
Total	40	100.	Total	35	100.	Total	24	100.

*8 Primary Neural Regions. **Bold** = Top tier; *Ital* = 2nd tier; Plain text = Bottom tier.

Visual-Spatial Unit Comparisons for Primary Regions

Visual-Spatial: Primary Region Unit Comparisons											
Spatial Cognition			**Insight-Intuition**			**Visual Arts**			**Working with Objects**		
Regions	ct	%	Regions	ct	%	Regions	ct	%	Regions	ct	%
Frontal Cortex	**43**	**35.**	**Subcortical**	**10**	**31.**	**Frontal Cortex**	**12**	**48.**	**Parietal Cortex**	**10**	**43.**
Parietal Cortex	*25*	*20.*	**Frontal Cortex**	**10**	**31.**	*Parietal Cortex*	*6*	*24.*	*Frontal Cortex*	*7*	*30.*
Temporal Cortex	*20*	*16.*	Parietal Cortex	4	12.	*Subcortical*	*4*	*16.*	Occipital Cortex	3	13.
Occipital Cortex	16	13.	Cingulate Cortex	3	9.	Temporal Cortex	1	4.	Temporal Cortex	3	13.
Cerebellum	5	4.	Cerebellum	2	6.	Occipital Cortex	1	4.			
Subcortical	5	4.	Occipital Cortex	2	6.	Cingulate Corte	1	4.			
Cingulate Cortex	4	3.	Temporal Cortex	1	3.						
Insular Cortex	2	1.									
Total	120	100	Total	32	100	Total	25	100	Total	23	100

*8 Primary Neural Regions. **Bold** =Top tier; *Ital* = 2nd tier; Plain text = Bottom tier.

Kinesthetic Unit Comparisons for Primary Regions

Kinesthetic: Primary Region Unit Comparisons											
Dexterity			**Whole Body**			**Body Awareness**			**Motor Cognition**		
Regions	ct	%	Regions	ct	%	Regions	ct	%	Regions	ct	%
Frontal Cortex	**25**	**37.**	**Parietal Cortex**	17	34.	**Frontal Cortex**	**21**	**48**	**Frontal Cort**	11	**55.**
Temporal Cortex	*11*	*16.*	**Frontal Cortex**	**16**	32.	*Parietal Cortex*	*10*	*23*	Parietal Cortx	6	30.
Parietal Cortex	*11*	*16.*	Subcortical	5	10.	Subcortical	4	9.	Cerebellum	3	15.
Cerebellum	7	10.	Cerebellum	5	10.	Insular Cortex	4	9.			
Subcortical	7	10.	Occipital Cortex	3	6.	Cingulate Cortex	2	4.			
Cingulate Cortex	4	6.	Temporal Cortex	2	4.	Cerebellum	2	4.			
Insular Cortex	2	3.	Cingulate Cortex	1	2.						
			Brainstem	1	2.						
Total	67	100	Total	50	100	Total	43	100	Total	20	100

*8 Primary Neural Regions. **Bold** = Top tier; *Ital* = 2nd tier; Plain text = Bottom tier.

Musical Unit Comparisons for Primary Regions

Musical: Primary Region Unit Comparisons											
Production			**Perception**			**Cognition**			**Melody-Pitch-Rhythm**		
Regions	ct	%	Regions	ct	%	Regions	ct	%	Regions	ct	%
Frontal Cortex	**95**	**43**	**Frontal Cortex**	**21**	**32**	**Frontal Cortex**	**10**	**35**	**Temporal Cortex**	**8**	**36**
Temporal Cortex	**43**	**19**	**Temporal Cortex**	**20**	**31**	*Temporal Cortex*	*7*	*25*	**Parietal Cortex**	**7**	**31**
Parietal Cortex	*23*	*10*	*Cerebellum*	*8*	*12*	*Parietal Cortex*	*6*	*21*	*Frontal Cortex*	*4*	*18*
Subcortical	*18*	*8*	*Subcortical*	*8*	*12*	Cerebellum	3	10	Insular Cortex	1	4
Cerebellum	*16*	*7*	*Parietal Cortex*	*6*	*9*	Occipital Cortex	1	3	Occipital Cortex	1	4
Cingulate Cortex	9	4	Insular Cortex	1	1	Subcortical	1	3	Cerebellum	1	4
Insular Cortex	8	3									
Occipital Cortex	5	2									
Total	217	100		64	100	Total	28	100	Total	22	100

*8 Primary Neural Regions. **Bold** = Top tier; *Ital* = 2nd tier; Plain text = Bottom tier.

Supplemental Information 4. Components of Extended Working Memory Matched with Multiple Intelligences

Working Memory – Extended Components Matched to Multiple Intelligences		
Component	**Description**	**MI Correlates**
Short Term Working Memory- Attention: Alerting and Orienting	"…a limited capacity system allowing the temporary storage and manipulation of information necessary for such complex tasks as comprehension, learning and reasoning (Baddeley, 2000) "Subjectively, a selective prefrontal focus on task-relevant information, with its accompanying dominant representation in sensory, motor, memory, motivational and other systems, would correspond to the state of controlled, active attention to this information, or, equivalently, to controlled, active maintenance in working memory. In this way, the prefrontal cortex carries out a central function in configuring a flexible cognitive system to address specific, current concerns." (p. 825, Duncan, 2001) **Arousal…** producing and maintaining optimal vigilance and performance during tasks…a warning signal to change from resting state…"(Posner, 2016) **Orienting…"..** the ability to prioritize sensory input by selecting a modality or location… (Posner, 2012) …is involved in attending to external signals regardless of sensory modality. (Posner & Rothbart, 2014) **Encoding Strategies** the working memory task used in this study is the reorganization of structured sequences into higher level spatial chunks." p. 363. (Bor, 2003) **Stable Set-Maintenance**: **cingulo-opercular** network provides stable 'set-maintenance' over the entire task epoch (Dosenbach, 2008) **Adaptive control**: "fronto-parietal control network… combines brain regions that **initiate attentional control in response to cues** …adjusts control settings… adjustment signals" (Dosenbach, 2008)	"…the normal human being is so constituted as to be sensitive to certain informational content: when a particular form of information is presented, various mechanisms in the nervous system are triggered to carry out specific operations upon it. And from the repeated use of, elaboration of, and interaction among these various computational devices, eventually flow forms of knowledge that we would readily term "intelligent…building upon "dumb" computational capacities, we may still end up with intelligent and even highly creative behavior" p. 279 Gardner, 1983/1993
WM Capacity	**Adaptive Coding Model**: "working memory, selective attention and control are simply three different perspectives on the same underlying processing function… **adaptability in itself implies selective** attention, or a selective emphasis on relevant inputs and the filtering out of irrelevant inputs…. frontal systems in some sense control or shape task-relevant processing elsewhere in the brain. The proposal is that, to achieve processing coherence, multiple brain systems share a strong tendency to converge to represent similar or related information … (p.824, Duncan, 2001) **Error Response**: …the cerebellum forms a separate but related cluster of regions that is interposed between **the fronto-parietal and cingulo-opercular** networks … the **cerebellum** sends error codes to both networks and/or that it receives error information\n from one or both of the control networks of the brain…. cerebellar regions displayed only error-related activity, consistent with the view that the cerebellum processes error information in the service of performance optimization (Dosenbach, 2008) "Working memory capacity refers to the maximal amount of information an individual can retain over a short interval in the absence of external stimulation" (Markett 2017) "the **superior intraparietal sulcus (IPS)** is a critical brain region that influences the variability of visual working memory precision between and within individuals under increased memory load, possibly in cooperation with perceptual systems of the **occipital cortex (V1)** (Weber, 2016) "Active rehearsal of the spatial sequence might be one such factor. In pure passive storage of visuo-spatial information, the capacity limit is about four items (Cowan, 2001). In span tasks the limit is typically seven to eight items, which is presumably due to the active rehearsal of the information. (p. 2172, Kingberg, 2006)	
	Visuospatial sketchpad … fractionable into separate visual, spatial and possibly kinaesthetic components,"	**Visual-spatial:** -mental
Visuospatial Passive Active storage Visual Spatial	Baddeley, 2000 "The spatial-span task, in which subjects retain information about the order and position of a number of objects, is a sensitive task to measure development of spatial working memory". (p. 2171, Klingberg, 2006) "Working memory processes can be divided into two categories, one being passive storage and the other being a more active process related to "executive control" or "controlled attention". Tasks requiring more controlled attention are more highly correlated with reasoning ability and intelligence." (p. 2171, Klingberg, 2006) "Smith & Jonides, 1997, observed a distinction between spatial working memory and memory for an object or pattern, such as an abstract shape." Baddeley, 2015. p. 94.	visualization -visual perception -three-dimensional objects -spatial awareness
Verbal	Phonological loop: "…to hold verbal and acoustic information using a temporary store and an articulatory rehearsal system" (Baddeley, 2000) "the reading span measure correlated reasonably well (.45) with a measure of language processing ability… Verbal SAT scores…. Working memory capacity for spatial thinking, was significantly correlated with spatial ability measures at .66 … This pattern of correlations is consistent with the view that spatial and verbal working memory may be supported by separate pools of cognitive resources." (Shah, 1996,) "Given that the latter three areas are known to be involved in the planning and production of speech (e.g., 10), we tentatively identified them as mediating a sub-vocal, rehearsal process; the posterior parietal area was thought to underlie a storage process … " (p. 12062, Smith, 1998)	Linguistic: -mental verbalization -receptive language understanding -oral speech -reading -writing
Episodic Buffer	"Baddeley has proposed separate 'slave system' buffers that allow for temporary retention of discrete information in working memory, including a visuospatial buffer and a phonological buffer. Logie and others have further decomposed the visuospatial buffer into separate visual and spatial buffers. The present fMRI results provide evidence for another type of buffer, namely, one that allows for temporary retention of integrated information." (Prabhakaran, 2000)	**Visual-spatial** -mental imagery -visual awareness -spatial awareness **Musical** -sounds -rhythms **Kinesthetic**
	"Evidence for the integrated storage of information from different modalities and systems comes from the small but significant impact of visual similarity on verbal recall, and from the **very substantial impact of meaning** on the immediate recall of sentences and prose passages … **a process or mechanism for synergistically combining information from various subsystems into a form of temporary representation**. Such a representation also offers a possible solution to the binding problem and the role of consciousness. The term 'episodic buffer' is proposed for this suggested fourth component of the working memory model" (Tillman, 2008) "The episodic buffer is assumed to be capable of **storing information in a multi-dimensional code** … The buffer serves as a modelling space that is separate from LTM, but which forms an important stage in long-term episodic learning. The component proposed is a buffer in that it serves as an interface between a range of systems, each involving a different set of codes. It is assumed to achieve this by using a common multi-dimensional code. (Baddeley) The buffer provides not only a mechanism for modelling the environment, but also for creating new cognitive representations, which in turn might facilitate problem-solving. (Baddeley, 2010)	-dexterity -large motor movements **Naturalist ?** -natural environment awareness -pattern recognition -awareness of living plants -awareness of animal life
Central Executive	"Neuropsychologists may then regard the **anterior cingulate** as a **central executor** that coordinates and integrates the task-oriented sensory, receptive and expressive language, alerting, working memory, response selection, motor planning, and motor response processes within the CNS." (Peterson) "…the task model is a form of working memory…goal neglect reflects a kind of limit in attentional or **working memory capacity.** This limit, however, is something rather different from the real-time limits of traditional attention and working memory… a limit in constructing and maintaining what we call a *task model*—a working-memory description of relevant facts, rules, and requirements used to **control current behavior**. It is this attentional limit, we propose, that underlies goal neglect and is	**Intrapersonal** -self-awareness -self-knowledge -self-management / judgment -management of feelings -metacognition -self-other people management -judgment / decision making (with logical-math)
	closely related to *g*" p. 140. (Duncan, 2008)	

	"...novel skills must be shaped by some explicit list of relevant **facts and rules**.... a central working memory builds up an accumulating model of knowledge bearing on a current task—**knowledge from the senses** and from long-term memory. Typically, this model includes both the current state of relevant aspects of the world, **goal states** to be achieved, and **candidate methods for achieving them.** The contents of this model represent the active body of knowledge that bears on current decision making…" (p. 140 Duncan, 2008) "...it is often proposed that the few chunks of working memory are closely related to the immediate contents of awareness. In contrast, **nobody would suppose that a whole set of instructions is kept immediately in awareness until the time the instructions are used**…. Our proposal is closer to Baddeley's (2000) "**episodic buffer**" (p. 417), a working memory component proposed to hold task relevant facts over relatively extended periods of time…. "…working memory has to include in addition to the temporary storage of information that we refer to as short-term working memory (ST-WM), another mechanism based on skilled use of storage in long-term memory (LTM) that we refer to as long-term working memory (LT-WM) (Ericsson, 1995)	
Executive Processing A single control unit or parallel / dual processing…	A Top-down cognitive control. "…this cognitive control view favors a single unified executive system in **which lateral prefrontal cortex** provides top-down control signals, guided by performance monitoring signals generated by **midline structures** …" (Peterson, Posner, 2012) "Using a sample of 4- to 11-year-olds, Alloway, Gathercole, and Pickering (2006) found that a model with two domain specific storage components and one domain-general executive component best fitted their data, **although separation of verbal and visuospatial executive components** also yielded an acceptable model." Tillman, 2008) "the suppression of a more automatic behavior (word reading) to perform a less	
	automatic one (color naming). Word-color interference is therefore regarded as a model for studying the **resolution of behavioral conflict and the regulation of impulse control**…" (Peterson).	
Domain-General	A specific network of prefrontal regions recruited to solve diverse cognitive problems. (Duncan, 2000)	
Executive Sub-skills	"executive processes are mediated by PFC and are involved in the regulation of processes operating on the contents of working memory. Although there is lack of consensus about a taxonomy of executive processes, there is some agreement that they include (i) **focusing attention on relevant information** and processes and inhibiting irrelevant ones ("attention and inhibition"); (ii)**scheduling processes** in complex tasks, which requires the switching of focused attention between tasks ("task management"); (iii) **planning a sequence of subtasks** to accomplish some goal ("planning"); (iv) updating and checking the contents of working memory to determine the next step in a sequential task ("monitoring"); (v) **coding representations in working memory for time and place of appearance** ("coding"). (Smith, 1999)	
Working Self	"… the goals of the working self form a subset of working-memory control processes organized into interconnected goal hierarchies that function to constrain cognition, and ultimately behavior, into effective ways of operating on the world" (p. 265, Conway, 2000).	**Intrapersonal**
Attention and impulse control	"… a parallel distributed processing model for word-color interference in which portions of the anterior cingulate cortex modify the strengths of multiple neural pathways used to read and name colors. Allocation of attentional resources is thought to modify pathway strengths by reducing cross-talk between information processing modules that subserve the competing demands of reading and color naming. …working memory regions thought to subserve functions, and we propose that the working memory demands derive from the need to monitor and update task demands and performance. Task demands are greater during the interference conditions,	**Intrapersonal**
	accounting for the prominence of activations in working memory" Peterson, 1999	

Self-Regulation Cognitive Emotional	'…resolving conflict among competing responses…important for self-regulation in middle childhood and beyond and efficiency correlates with school performance…serves as a means of self-regulation through control of brain networks involved in emotion, cognition and behavior…" (Posner & Rothbart & Tang, 2013) "The ability to control our thoughts, feelings, and behavior in developmental psychology is called self-regulation; with adults it is often called self-control…" (Posner) "The more dorsal area of the anterior cingulate has been shown to be active primarily in cognitive tasks like the Stroop. However, when tasks have a more emotional component they activate a more ventral part of the cingulate" (Posner, 2007) "Emotional self-regulation refers to the heterogeneous set of processes by which individuals influence, consciously and voluntarily, which emotions they have, when they have them, and how they experience and express these emotions" (Beauregard)	**Intrapersonal** **Interpersonal** - ?
Relational Integration	"..working memory as a system for building relational representations through temporary bindings between component representations." Oberauer, et al. 2008	Logical-mathematical
Working Memory and Real World performances Academic skills School achievement Intelligence	"Complex working memory and performance on tasks involving both the written and spoken comprehension of language show robust and consistent associations in both children and adults. Recent evidence indicates that this is a genuine causal link rather than a simple association. Individuals with good working-memory abilities are also particularly good at acquiring the conceptual aspects of vocabulary acquisition…" (p. XX, Gathercole) "Investigations of the cognitive underpinnings of higher-order cognitive abilities have drawn researchers' attention to the processes of working memory (WM), which consistently have been shown to be strongly linked to reading comprehension, mathematical ability, and fluid intelligence in both children and adults" (Tillman, 2007, p. 394). "…the results of the metaanalysis and subsequent analyses support a conclusion that WM is not isomorphic to g, Gf, Reasoning, or any other group factor of intelligence….high-quality estimates of general intelligence (or g) cannot be derived only from a single nonverbal reasoning scale (such as the Raven)…**it may be that WM is related to executive control and attentional capacity, but the construct does not account for all of the individual differences in these capabilities. … WM does not adequately sample the range of executive control and attention. " (p. 44)** Ackerman, 2005) "It was concluded that the executive processes, referred to as executive attention by Engle and Kane, constitute the primary WM component in the relation between measures of WM and intelligence". (Tillman, 2008). "…with respect to individual differences, there is little or no support for a general… ability or for a general vigilance ability; and the existence of a general selective-attention ability seems unlikely. Instead, a number of specific abilities, linked to specific task variables and information-processing demands, appear to be involved to varying degrees in the performance of all of these tasks. (p. 432?) (Ackerman, et al. p. 45)	Linguistic Logical-mathematical

Supplemental Information 5. Neural Organization Framework

Frontal Cortex
- Motor Cortex
  - Primary Motor Cortex (BA 4)
    - Precentral Gyrus
    - Paracentral Lobule
  - Premotor Cortex (BA 6)
    - Dorsal Premotor
  - Supplementary Motor Area (BA 6)
  - Pre-supplementary Motor Area (pSMA) (BA4
  - Frontal Eye Field (BA 8)
- Prefrontal Cortex
  - Anterior Prefrontal Cortex (BA 10)
  - Dorsolateral Prefrontal Cortex (Functional Structure) (BA 9, 46)
  - Orbitofrontal Cortex (BA 10, 11, 12, 47) / Ventromedial Prefrontal Cortex
    - Medial Prefrontal Cortex (MPFC)
      - Dorsalmedial PFC
- Superior Frontal Gyrus
- Middle Frontal Gyrus
  - Dorsolateral Prefrontal Cortex

Inferior Frontal Gyrus / Ventrolateral Prefrontal Cortex
- Pars Opercularis (BA 44) / Broca's Area Mirror Neurons
- Pars Triagularis (BA 45) / Broca's Area Mirror Neurons
- Pars Orbitalis (BA 47)

Parietal Cortex
- Superior Parietal Lobule
  - Posterior Superior Parietal Lobule
    - Precuneus
- Inferior Parietal Lobule (BA 39, 40)
  - Anterior Inferior Parietal Lobule
    - Supramarginal Gyrus (BA 40)
  - Posterior Inferior Parietal Lobule
    - Angular Gyrus (BA 39)
- Medial Parietal Cortex

- Anterior Parietal Lobe
  - Postcentral Gyrus = Primary Somatosensory Cortex (BA 1, 2, 3)
    - = Sensorimotor

Posterior Parietal Lobule (BA 5, 7)

Primary Auditory Cortex (BA 41, 42)

Temporal Cortex

Amygdala

Anterior Temporal Cortex (BA 15) / Temporopolar Area (BA 38)

Superior Temporal Cortex
- Superior Temporal Gyrus (BA 22)
  - Caudal Wernicke's Area
  - Primary Auditory Cortex / A1 Heshchl's Gyrus
  - Superior Temporal Sulcus
- Inferior Temporal Cortex
  - Inferior Temporal Gyrus (BA 20)
  - Inferior Temporal Sulcus
- Middle Temporal Gyrus (BA 21)
- Medial Temporal Lobe
  - Hippocampus
  - Parahippocampal Gyrus
    - Anterior Parahippocampal Gyrus
      - Perirhinal Cortex (BA 35)
      - Entorhinal Cortex (Caudal MTL)
        - Dorsal Entorhinal (BA 34)
- Posterior Parahippocampal Gyrus
- Parahippocampal Cortex
    - Fusiform Gyrus
    - Medial Fusiform Gyrus Visual Word Form Area

Occipital Cortex
- Primary Visual Cortex / Striate Cortex / V1 / Cuneus (BA 17)
- Secondary Visual Cortex / Extrastriate Cortex / V2 (BA 18)
- Peristriate (BA 19) (lingual gyrus, cuneus, lateral occipital gyrus, superior occipital gyrus)
- Associative Visual Cortex / V3 / V4/ V5

Cingulate Cortex / Cingulate Gyrus
- Anterior Cingulate Cortex (BA 24, 32, 33)
  - Ventral Anterior Cingulate Cortex (BA 24)
  - Dorsal Anterior Cingulate Cortex (BA 32)

Posterior Cingulate Cortex (BA 23, 31)
- Dorsal Posterior Cingulate Cortex (BA 31)
- Retrosplenial Cortex (BA 29, 30)

Insular Cortex (BA 13, 14, 16)
- Anterior Insular Cortex
- Posterior Insular Cortex

Subcortical
- Basal Ganglia
  - Striatum
    - Dorsal Striatum
      - Putamen
      - Caudate (Head, Body, Tail)
    - Ventral Striatum
      - Nucleus Accumbens
      - Olfactory Tubercle
  - Pallidum
    - Globus Pallidum
    - Ventral Pallidum
  - Substantia Nigra
  - Subthalamic Nuclei
- Brainstem

Midbrain
- Tectum
- Tegmentum
  - Cerebral Aqueduct
    - Periaqueductal Gray
- Cerebral Peduncles
- Pons
- Medulla
- Thalamus Hypothalamus

Cerebellum
Anterior Cerebellum
Posterior Cerebellum

Other notes on data coding:
Lateral sulcus = Sylvian Fissure
Intraparietal Sulcus: divides superior and inferior parietal lobules
Anterior Temporal Cortex = Temporal Pole
Anterior Frontal Cortex = Frontal Pole = Frontopolar Cortex = Rostrolateral Prefrontal Cortex
BA 25 = Subgenual Area
Insular Cortex = Insula = Insular Lobe

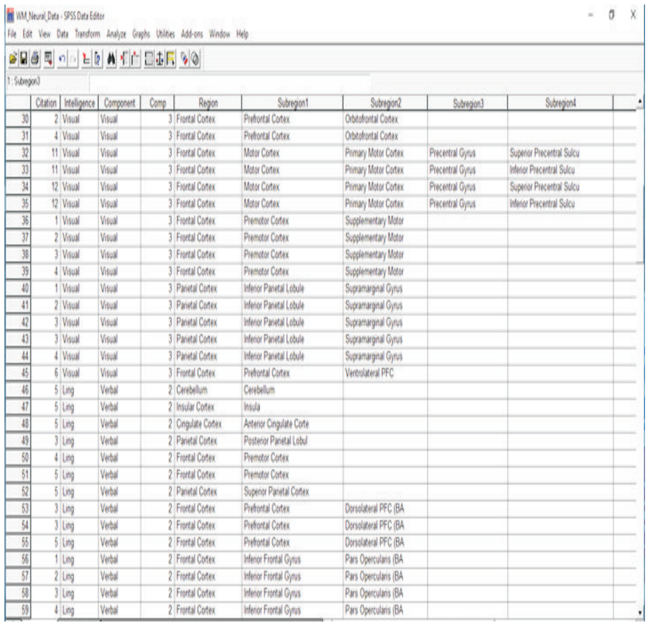
Multi-Regions These are citations that encompass a number of cortical or subcortical regions, and therefore do not fit singly into the categories outlined above.
Audiovisual Motor Stream
Cerebellothalamic
Cortical Midline Structures (CMS)
Cortico Striatal Cerebellar
Corticopontine
Default Mode Network
Dorsal Stream
Ventral Stream
Echo Neurons
Frontal Executive Network
Frontomedian Regions
Frontoparietal Cortex
Frontotemporal Cortex
Language Areas
Limbic System
Mirror Neuron System
Motor Areas
Occipitoparietal Cortex
Occipitotemporal Cortex
Olfactory Cortex
Parietotemporal Cortex
Pontocerebellar
Sensorimotor Cortex
Sensory Cortex
Temporoparietal Junction
Thalamocortical

Supplemental Information 6. Neural Correlates of Working Memory Capacity and Matched Multiple Intelligences

Working Memory and Multiple Intelligences Neural Correlates	
WM Component	**Neural Correlates**
Verbal	Brodmann 40 and 44 (Baddeley) Posterior left, 40; Broca's 44, 6 Premotor cortex, supplementary motor (6) (Gathercole, 1999, p. 412) Left BA40 parietal cortex; L. BA 44 (Broca's); L. 46 of Prefrontal cortex; Right BA7 and BA 40 of a parietal and BA 46 & BA9 of PFC.(Smith, 1996, p. 16-17)
Visuospatial	Right hemisphere 6, 19, 40, and 47 (Baddeley) Inferior prefrontal, r, 47' Anterior occipital,r,19, 40 Posterior parietal, r, 6 Premotor (Gathercole, 1999, p. 412) BA 40, r. parietal; r. premotor; BA46 r. dorsolateral prefrontal cortex; BA7r. posterior parietal cortex. Left BA 7 and BA40 of parietal; BA46 and SMA (Smith, 1996, p. 16) "Spatial memory activates more dorsal or upper regions of the brain whereas object memory tends to be more concentrated on lower or ventral areas." P. 94. Baddeley and Smith and Jonides, 1999.
Episodic Buffer	"I would not expect the buffer to have a single unitary anatomical location; given its putative importance, some redundancy would be biologically useful in making the system more robust. However, **frontal areas are very likely to be important for both the central executive and the episodic buffer"(Baddeley)**
WM Capacity	"intraparietal sulcus is the central hub of the **fronto-parietal network** (Fox et al. 2005). This network has already been linked to general cognitive ability…the intraparietal sulcus does not store information itself, IPS is a resting-state correlate of a **working memory related control processes**… Association between working memory capacity and the intraparietal connectivity at rest reflect between-participant **efficiency** by which this region can be recruited during task processing. (Markett)
Central Executive / Executive Attention	'Whereas **posterior cortical regions** seem to specialize in the type of information held in working memory. , several findings suggest that **prefrontal** areas have a special role in integrating different types of information in working memory.(Prabhakaran) **Frontal lobe** **Dorsal lateral prefrontal cortex, left and bilateral; BA9, 10, 44, 45, 46** **Prefrontal cortex** as a region of polymodal sensory convergence from **posterior cortical areas (parietal, temporal and visual)**. Works to maintain different types of information (letters, objects, locations, faces, etc.) in working memory. (Prabhakaran)
	"**prefrontal** activation in the present study may reflect one solution to the binding problem in the human brain—the problem of integrating the outputs of multiple, specialized processing pathways." (Prabhakaran, 2000)
A single control unit **and / or** **parallel** **processing…**	A top-down cognitive control. Lateral prefrontal cortex… midline structures… (see Peterson, Posner) "…top-down control to several prefrontal regions, mainly the **dorsolateral prefrontal cortex (dlPFC)** and **dorsal anterior cingulate cortex/medial superior frontal cortex (dACC/msFC).** (Koechlin) "**anterior cingulate**… task integrator" (Peterson) "…this cognitive control view favors a single unified executive system in **which lateral prefrontal cortex** provides top-down control signals, guided by performance monitoring signals generated by **midline structures**. (Peterson, Posner, 2012) "the suppression of a more automatic behavior (word reading) to perform a less automatic one (color naming). Word-color interference is therefore regarded as a model for studying the **resolution of behavioral conflict and the regulation of impulse control**…" (Peterson). "Neuropsychologists may then regard the **anterior cingulate** as a **central executor** that coordinates and integrates the task-oriented sensory, receptive and expressive language, alerting, working memory, response selection, motor planning, and motor response processes within the CNS."(Peterson)
Dual-Networks Components Plus, error detection >Adaptive >Set Maintenance >Error Responses	**Adaptive control**: "fronto-parietal control network… combines brain regions that initiate attentional control in response to cues …adjusts control settings… adjustment signals" (Dosenbach **Stable Set-Maintenance**: cingulo-opercular network provides stable 'set-maintenance' over the entire task epoch (Dosenbach) **Error Response**: the cerebellum forms a separate but related cluster of regions that is interposed between the fronto-parietal and cingulo-opercular networks … the cerebellum sends error codes to both networks and/or that it receives error information\n from one or both of the control networks of the brain…. cerebellar regions displayed only error-related activity, consistent with the view that the cerebellum processes error information in the service of performance optimization (Dosenbach) **Adaptive control:** **Frontal-parietal** includes parts of the dorsal attention network (DAN) and dorso lateral prefrontal cortex (dlPFC) and Intraparietal Lobule (IPL)
	Dorsal frontal cortex (dFC), Intraparietal sulcus (IPS), precuneus and middle cingulate cortex (mCC). (Dosenbac **Stable Set Maintenance:** cingulo-opercular network includes the anterior prefrontal cortex (aPFC), anterior insula/frontal operculum (aI/fO), dorsal anterior cingulate cortex/medial superior frontal cortex (dACC/msFC) and thalamus" (Doesenbach) The ACC and bilateral aI/fO carry particularly large numbers of von Economo neurons (Dosenbach) **Error Response**: "cerebellar regions displayed only error-related activity, consistent with the view that the cerebellum processes error information in the service of performance optimization .. the cerebellar error regions were connected to the dlPFC and IPL in the fronto-parietal network, and to the thalamus in the cingulo-opercular network" (Dosenbach)
Domain-General	The central executive …implicated in allocation of attention resources…" (Tillman) "a single factor looms above the others in generality or pervasiveness. We presume that this central factor is responsible for influencing performance in a broad variety of

	cognitive and learning tasks. In the conventional abilities model, the central factor is reasoning ability, or general fluid intelligence *(Gy)*. Reasoning ability is traditionally "considered to be at or near the core of what is *intelligence"* (Carroll, 1989, p. 56) (K & Christal) "The **right prefrontal activation associated with the integration of verbal and spatial information** is in agreement with meta-analyses showing **right prefrontal involvement in both spatial and nonspatial** working memory. In contrast, **left prefrontal regions show involvement only in nonspatial** working memory. Thus, **right prefrontal regions seem to have a flexible representational architecture that processes both spatial and nonspatial information**. Posterior activations have been more material specific, with specific areas in **parietal and temporal regions involved either in verbal or spatial working memory** (Prab)
Executive Sub-skills	"executive processes are mediated by PFC and are involved in the regulation of processes operating on the contents of working memory. Although there is lack of consensus about a taxonomy of executive processes, there is some agreement that they include (i) **focusing attention on relevant information** and processes and inhibiting irrelevant ones ("attention and inhibition"); (ii)**scheduling processes** in complex tasks, which requires the switching of focused attention between tasks ("task management"); (iii) **planning a sequence of subtasks** to accomplish some goal
	("planning"); (iv) updating and checking the contents of working memory to determine the next step in a sequential task ("monitoring"); (v) **coding representations in working memory for time and place of appearance** ("coding"). (Smith, 1999) "the executive process of **attention and inhibition** is recruited whenever two processes are in conflict…. "substantial variation in regions of activation, although one broad region is the **anterior one third of cingulate cortex** (31). Activations in the anterior cingulate have been obtained in other experiments that induce a conflict between processes or response tendencies as well (32). These studies suggest that the anterior cingulate may be involved in the resolution of cognitive conflict.(Smith, 1999)
attention and impulse control	"' *a parallel distributed processing model for word-color interference in which portions of the anterior cingulate cortex modify the strengths of multiple neural pathways used to read and name colors. Allocation of attentional resources is thought to modify pathway strengths by reducing cross-talk between information processing modules that subserve the competing demands of reading and color naming.* …working memory regions thought to subserve functions, and we propose that the working memory demands derive from the need to monitor and update task demands and performance. Task demands are greater during the interference conditions, accounting for the prominence of activations in working memory" Peterson. "…activations in the **mesial Parieto-occipital region at the border of areas 7 and 19**, the **left inferior parietal area 39, dorsolateral prefrontal area 46**, the **left hippocampus, and the left premotor/motor region**. …**rostral anterior cingulate and mesial frontal regions (areas 24 and 32)"** (Peterson)
Self-Regulation **Cognitive** **Emotional**	"The ability to control our thoughts, feelings, and behavior indevelopmental psychology is called self-regulation; with adults it is often called self-control…" Posner, The more dorsal area of the anterior cingulate has been shown to be active primarily in cognitive tasks like the Stroop. However, when tasks have a more emotional component they activate a more ventral part of the cingulate" (Posner, 2007) "Emotional self-regulation refers to the heterogeneous set of processes by which individuals influence, consciously and voluntarily, which emotions they have, when they have them, and how they experience and express these emotions" (Beauregard) **Dorsal anterior cingulate for cognitive self regulation and ventral part of the anterior cingulate for emotion…**(Posner, 2007) "..emotional self-regulation may be normally implemented by a neural circuit consisting of several regions of the **prefrontal cortex (PFC) [e.g., orbitofrontal PFC, dorsolateral PFC, anterior cingulate cortex (ACC)], and of**
	subcortical limbic structures, such as the amygdala and the hypothalamus. (Beauregard)

Supplemental Information 7. WM Neural Database Sample


WM_Neural_Data - SPSS Data Editor
File Edit View Data Transform Analyze Graphs Utilities Add-ons Window Help
1 : Subregion3

	Citation	Intelligence	Component	Comp	Region	Subregion1	Subregion2	Subregion3	Subregion4
30	2	Visual	Visual	3	Frontal Cortex	Prefrontal Cortex	Orbitofrontal Cortex		
31	4	Visual	Visual	3	Frontal Cortex	Prefrontal Cortex	Orbitofrontal Cortex		
32	11	Visual	Visual	3	Frontal Cortex	Motor Cortex	Primary Motor Cortex	Precentral Gyrus	Superior Precentral Sulcu
33	11	Visual	Visual	3	Frontal Cortex	Motor Cortex	Primary Motor Cortex	Precentral Gyrus	Inferior Precentral Sulcu
34	12	Visual	Visual	3	Frontal Cortex	Motor Cortex	Primary Motor Cortex	Precentral Gyrus	Superior Precentral Sulcu
35	12	Visual	Visual	3	Frontal Cortex	Motor Cortex	Primary Motor Cortex	Precentral Gyrus	Inferior Precentral Sulcu
36	1	Visual	Visual	3	Frontal Cortex	Premotor Cortex	Supplementary Motor		
37	2	Visual	Visual	3	Frontal Cortex	Premotor Cortex	Supplementary Motor		
38	3	Visual	Visual	3	Frontal Cortex	Premotor Cortex	Supplementary Motor		
39	4	Visual	Visual	3	Frontal Cortex	Premotor Cortex	Supplementary Motor		
40	1	Visual	Visual	3	Parietal Cortex	Inferior Parietal Lobule	Supramarginal Gyrus		
41	2	Visual	Visual	3	Parietal Cortex	Inferior Parietal Lobule	Supramarginal Gyrus		
42	3	Visual	Visual	3	Parietal Cortex	Inferior Parietal Lobule	Supramarginal Gyrus		
43	3	Visual	Visual	3	Parietal Cortex	Inferior Parietal Lobule	Supramarginal Gyrus		
44	4	Visual	Visual	3	Parietal Cortex	Inferior Parietal Lobule	Supramarginal Gyrus		
45	6	Visual	Visual	3	Frontal Cortex	Prefrontal Cortex	Ventrolateral PFC		
46	5	Ling	Verbal	2	Cerebellum	Cerebellum			
47	5	Ling	Verbal	2	Insular Cortex	Insula			
48	5	Ling	Verbal	2	Cingulate Cortex	Anterior Cingulate Corte			
49	3	Ling	Verbal	2	Parietal Cortex	Posterior Parietal Lobul			
50	4	Ling	Verbal	2	Frontal Cortex	Premotor Cortex			
51	5	Ling	Verbal	2	Frontal Cortex	Premotor Cortex			
52	5	Ling	Verbal	2	Parietal Cortex	Superior Parietal Cortex			
53	3	Ling	Verbal	2	Frontal Cortex	Prefrontal Cortex	Dorsolateral PFC (BA		
54	3	Ling	Verbal	2	Frontal Cortex	Prefrontal Cortex	Dorsolateral PFC (BA		
55	5	Ling	Verbal	2	Frontal Cortex	Prefrontal Cortex	Dorsolateral PFC (BA		
56	1	Ling	Verbal	2	Frontal Cortex	Inferior Frontal Gyrus	Pars Opercularis (BA		
57	2	Ling	Verbal	2	Frontal Cortex	Inferior Frontal Gyrus	Pars Opercularis (BA		
58	3	Ling	Verbal	2	Frontal Cortex	Inferior Frontal Gyrus	Pars Opercularis (BA		
59	4	Ling	Verbal	2	Frontal Cortex	Inferior Frontal Gyrus	Pars Opercularis (BA		

Supplemental Information 8. Summaries of Programs and Research that Focus on the Relationship between Multiple Intelligences and Working Memory

Note. Summaries of exemplar programs that focus on one of the multiple intelligences are provided below. Also included are several research reports that examine the neural relationship between the various intelligences and working memory. Not all of these innovative programs are equally successful but represent creative thinking about new approaches to solving last standing problems. These are provided to illustrate and inspire researchers and practitioners to continue to explore these relationships

Intrapersonal.

Tang, Y. et al. (2012). Improving Executive Function and its Neurobiological Mechanisms through a Mindfulness-Based Intervention: Advances within the Field of Developmental Neuroscience. Child Dev Perspect. 6(4): 361366. doi:10.1111/j.1750-8606.2012.00250.x.

Tang, Y. et al. (2008) Short-term meditation training improves attention and self-regulation. PNAS. 104 (43, 17152 17156.

These two studies examined the effectiveness of meditation training and mindfulness-based interventions to improve executive functions, attention and self-regulation.

The authors concluded:

"5 days of mediation practice … shows significantly better attention and control of stress than a similarly chosen control group . . .p. 17152. Mindfulness-based interventions made improvements in specific EF components, and uniquely highlight the role of neural circuitry specific to the ACC and the autonomic nervous system…" pg. 6

Interpersonal.

Ybarra, O. et al. (2008). Mental exercising through simple socializing: Social interaction promotes general cognitive functioning. Pers Soc Psychol Bull 2008; 34; 248.

This study examined the relationship between social interaction and cognitive functioning.
The authors concluded:

“the current findings fit with the emphasis in the social cognition literature on the role of
general processing resources in person perception and judgment (Lieberman et al., 2002). They also fit with recent research showing real practice-related changes in brain substrates underlying such fundamental functions as attention, working memory, and processing speed.” P. 255.

Musical.
Pallesen, K.J.; Brattico, E.; Bailey, C.J.; et al. (2010). Cognitive control in auditory working memory is enhanced in musicians." PLoS One. v. 5 p. e11120. 2010.
This study compared the performance and neural activation patterns between musicians and non-musicians on challenging Working Memory tasks.
The authors concluded:
“We tested the hypothesis that musicians nonetheless would perform better, and that differential brain activity would mainly be present in cortical areas involved in cognitive control such as the lateral prefrontal cortex. The musicians performed better as reflected in reaction times and
error rates. Musicians also had larger BOLD responses than non-musicians in neuronal networks that sustain attention and cognitive control, including regions of the lateral prefrontal cortex, lateral parietal cortex, insula, and putamen in the right hemisphere, and bilaterally in the posterior dorsal prefrontal cortex and anterior cingulate gyrus. The relationship between
the task performance and the magnitude of the BOLD response was more positive in musicians than in non-musicians, particularly during the most difficult working memory task. The results confirm previous findings that neural activity increases during enhanced working memory performance. The results also suggest that superior working memory task performance in musicians rely on an enhanced ability to exert sustained cognitive control. This cognitive benefit in musicians may be a consequence of focused musical training.” P. 11120.

Hsu, C, Cheng, C. & Chiu, Y. (2017). Analyze the beta waves of electroencephalogram signals from young musicians and non-musicians in major scale working memory task. Neuroscience Letters 640, 42 46.
This study developed a feature analysis method of EEG to differentiate between musicians and non-musicians while performing a complex Working Memory task.
The authors concluded: The musicians had a faster response speed, a higher response intensity, and a higher response power. The EEG beta wave responses of musicians shifted more rapidly than those of non-musicians and their psychological states changed from tense to relaxed more rapidly, too. The musicians were more focused and sensitive to tasks than the non-musicians. The improved working memory of musicians has been associated with greater brain activities in the right lateral prefrontal cortex, the right lateral parietal cortex, the bilateral posterior dorsal prefrontal cortex, and the bilateral anterior cingulate gyrus, as well as larger P300 amplitude (George and Coch, 2011).” P. 45.

George, E.M., Coch, D. (2011). Music training and working memory: an ERP study, Neuropsychologia 49 (5) 10831094, http://dx.doi.org/10.1016/j.neuropsychologia.2011.02.001.
“Using event-related potentials (ERPs) and a standardized test of working memory, we investigated both neural and behavioral aspects of working memory in college-aged, non-professional musicians and non-musicians. Behaviorally, musicians outperformed non-musicians on standardized subtests of visual, phonological, and executive memory. ERPs were recorded in standard auditory and visual oddball paradigms (participants responded to infrequent deviant stimuli embedded in lists of standard stimuli).
Electrophysiologically, musicians demonstrated faster updating of working memory (shorter latency P300s) in both the auditory and visual domains and musicians allocated more neural resources to auditory stimuli (larger amplitude P300), showing increased sensitivity to the auditory standard/deviant difference and less effortful updating of auditory working memory. These findings demonstrate that long-term music training is related to improvements in working memory, in both the auditory and visual domains and in terms of both behavioral and ERP measures.”

Vandervert, L. (2015). How music training enhances working memory: a cerebrocerebellar blending mechanism that can lead equally to scientific discovery and therapeutic efficacy in neurological disorders. Cerebellum & Ataxias, 2 11.
This study examined the neural bases for the relationship between music training and Central Executive functions. The authors concluded:

“It is concluded that the entire framework of the central executive structure of working memory is a product of the cerebrocerebellar system which can, through the learning of internal models, incorporate the multi-dimensional rigor and volitional-control demands of music training and, thereby, enhance voluntary control. It is further concluded that this cerebrocerebellar view of the music training-induced enhancement of central executive control in working memory provides a needed mechanism to explain both the highest level of scientific discovery and the efficacy of music training in the remediation of neurological impairments” p. 1.

Visual-spatial.
Peretz, C., Korczyn, A. D., Shatil, E., Aharonson, V., Birnboim, S., & Giladi, N. (2011). Computer-based, personalized cognitive training versus classical computer games: A randomized double-blind prospective trial of cognitive stimulation. Neuroepidemiology, 36(2), 9199.
This study examined the effects of computerized cognitive training on working memory for older adults.

The authors concluded

"…personalized cognitive training was significantly more effective than playing games in improving visuospatial working memory…" p. 91.

Klingberg, T. (2006). Development of a superior frontal-intraperietal network for visuo-spatial working memory. Neuropsychologia, 44, 2171 2177.

This study investigated changes in visuo-spatial working memory throughout childhood and adolescense.

The authors concluded

:… Furthermore, the degree of white matter maturation is positively correlated with the degree of cortical activation in the frontal and parietal regions. This suggests that during childhood and adolescence, there is development of networks related to specific cognitive functions, such as visuo-spatial working memory. These networks not only consist of cortical areas but also the white matter tracts connecting them. For visuo-spatial working memory, this network could consist of the superior frontal and intraparietal cortex." P. 2171.

Toril P, Reales JM, Mayas J and Ballesteros S (2016) Video Game Training Enhances Visuospatial Working Memory and Episodic Memory in Older Adults. Front. Hum. Neurosci. 10:206. doi: 10.3389/fnhum.2016.00206

This study investigated the effects of video game training on the visuospatial working memory (WM) and episodic memory of healthy older adults.

The authors concluded

"… we found significant enhancements after training in the trained group and no change in the control group in two computerized tasks designed to assess visuospatial WM, namely the Corsi blocks task and the Jigsaw puzzle task. The episodic memory and short-term memory of the trainees also improved. Gains in some WM and episodic memory tasks were maintained during a 3-month follow-up period" p. 206.

Logical-mathematical.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. (2008). Improving fluid intelligence with training on working memory. PNAS 105, (19), 6829 6833.

This study examined the impact of training working memory to measures of fluid intelligence (problem-solving).

The authors concluded:

"…our findings are of general significance because they provide evidence for enhancement of
fluid intelligence by cognitive training different from training the test itself. The finding that cognitive training can improve Gf is a landmark result because this form of intelligence has been
claimed to be largely immutable." P. 6832.

Naturalist.

Gee, N., Friedmann, E., Stendahl, M., Fisk, A. & Coglitore, V. (2014). Heart Rate Variability During a Working Memory Task: Does Touching a Dog or Person Affect the Response? Anthrozoös Vol. 27 , 4.

The goal of this study… "…study was designed to evaluate the effect of touching a
dog on stress responses to a working memory task (WMT). Heart rate variability (HRV) responses to a WMT while touching a dog were compared with responses while touching a stuffed dog and a person.

The authors concluded:

"…There also were no significant interactions, indicating that the stress response to the memory task did not differ when the participants were touching the three different co-participants. Touching a dog did not reduce arousal in response to a stressful memory task. This research suggests that a dog may not be effective at reducing stress responses to this type of stressor." P. 513.

Kobayashi, Ai (2017). The Effects of Touching and Stroking a Cat on the Inferior Frontal Gyrus in People". Anthrozoös (0892-7936), 30 (3), p. 473. DOI: 10.1080/08927936.2017.1335115

This study examined the effects of stroking a cat on the prefrontal cortex especially the inferior frontal gyrus (IFG) and emotional responsiveness.

The authors concluded:

"The integral values of the L-IFG in females during contact with a real cat were significantly greater than those in males, indicating that they nonverbally communicated with the cat. Right handed people are left-cerebrally dominant for language (Corballis et al., 2012). Therefore, it is conceivable that the effect of nonverbal communication appears in the L-IFG. Also, the IFG is activated when humans look at facial expressions and gestures (Grosbras et al., 2012). Thus, this finding indicates that females reacted to the cat's response more than males did, and communicated this nonverbally….The integral values of the L-IFG in females correlated positively with the number of strokes. Consequently, the stroking might have influenced the positive mood, resulting in the greater integral values in the L-IFG".. p.13

Gee, N., Friedmann, E., Coglitore, V., Fisk, A. & Stendahl, M. (2015). Does Physical Contact with a Dog or Person Affect Performance of a Working Memory Task? Anthrozoös : A multidisciplinary journal of the interactions of people and animals Volume 28, Issue 3, 483-500.

"The current study was constructed to examine whether the presence of a dog is an asset in adult cognition, and whether touching the dog is related to any such benefit. Two perspectives were examined: performance of a WM task and physiological arousal during that task." P.

“The authors concluded:

“In this study WM performance improved when a dog or a human was present during task performance, but the requirement to maintain physical contact with that dog or human, particularly the dog, was detrimental to WM performance. … In the current study, the dog conditions did not result in improved WM performance when compared with the human conditions, for either the touch or no-touch conditions. P.496.

“The results of the current study, combined with those of previous research, are allowing us to begin to understand the circumstances under which the presence of a dog is beneficial to human cognition and thus to academic performance. As more and more educators begin to incorporate animals into their classrooms, as a way of meeting the educational and developmental goals of their students (Uttley 2013), this type of research provides essential guidance as to the ways in which dogs can be an asset to learning and not a distraction.” P. 497

Henry, C. & Cowley, S.. (2015). The Psychological and Physiological Effects of Using a Therapy Dog in Mindfulness Training. Anthrozoös Volume 28, 2015 - Issue 3 Pages 385-402 http://dx.doi.org/10.1080/08927936.2015.1052272

“It was hypothesized that AAT would complement mindfulness-based interventions because the therapy dog will provide a focus for attention to the current experience and exemplify acceptance and “being,” enabling the understanding and practice of the main aspects of mindfulness.” P. 385

The authors concluded

“No significant difference was found between the control and experimental groups, indicating that interaction with a therapy dog had no impact on symptom reduction, skill acquisition, or client satisfaction in the current study. However, moderate to large effect size estimates indicate clinically significant differences between groups, with higher ratings for the MBSR + AAT group on therapist efficacy, recommending the training, and participating in future treatment.”. P. 385.

Kinesthetic.

Erickson, K., Hillman, C. and Kramer, A. (2015). Physical activity, brain, and cognition. Behavioral Sciences 4: 27 32.

This study examined the effects of physical activity and fitness on brain and cognition in children and older adults.

The authors concluded:

“Research in children finds that higher fit and more active preadolescent children show greater hippocampal and basal ganglia volume, greater white matter integrity, elevated and more efficient patterns of brain activity, and superior cognitive performance and scholastic achievement. Higher fit and more physically active older adults show greater hippocampal, prefrontal cortex, and basal ganglia volume, greater functional brain connectivity, greater white matter integrity, more efficient brain activity, and superior executive and memory function” p. 27.

Dalziell, A., Boyle, J., & Mutrie, N. (2015). Better Movers and Thinkers (BMT): An Exploratory Study of an Innovative Approach to Physical Education. Europe's Journal Of Psychology, 11(4), 722-741. doi:10.5964/ejop.v11i4.950

Supplemental Information 9. Neuroscientific Evidence Supporting the Validity of MI Theory - Summary

- Quoted from Bridging between IQ and Multiple Intelligences via Neuroscience Jrnl of Intelligence

A main criticism of MI is that it lacks empirical, experimental evidence of its validity. General intelligence is considered to be valid because there is a wealth of test data amassed for more than 100 years while there are no tests to measure the eight intelligences. Unrecognized by most researchers are the sizable number of brain studies that are matched to the multiple intelligences. This is a trove of scientific data scattered among many journals that are unread and largely incomprehensible to most non-neuroscientists-- until recently (1, 2, 3, 4)

Using a rational-empirical methodology, more than 500 studies of brain function (largely fMRI experiments) were matched to the skills and abilities integral to each of the eight intelligences. It is remarkable how well aligned so many neuroscience studies are with the core skills for each intelligence. Validity was examined from five different angles. Five to ten studies of each core ability per intelligence were included to maximize reliability.

The first question investigated the localization of neural cognitive functions for each intelligence. Analyses of over 318 reports indicates that all eight of the proposed intelligences possess coherent neural architectures (2). These clearly identifiable frameworks are comprised of structures with known cognitive correlates that are well-aligned with the core behavioral components for each of the multiple intelligences. The neural evidence for the multiple intelligences is as robust as the most widely accepted neural models underpinning general intelligence. The neural relationship between MI and general intelligence is as predicted by MI theory where IQ is most closely associated with the logical-mathematical and linguistic intelligences

The second question investigated 417 studies examining the neural correlates for specific skill units within seven intelligences (Naturalist not included due to a paucity of data). Neural activation patterns demonstrate that each skill unit has its own unique neural underpinnings as well as neural features that are shared with other skill units within its designated intelligence. These patterns of commonality and uniqueness provide a richly detailed neural architecture in support of MI theory as a detailed, scientific model of human intelligences.

The third investigation examined the neural differences among groups of people of varying ability levels for seven intelligences. This study of over 420 reports found that there are observable and meaningful differences in the neural activation patterns among groups with three levels of ability: skilled, typical, and impaired. These differential patterns are evidenced in four levels of brain analysis: primary regions, sub-regions, particular structures, and multi-region activations. These data show that there are distinctive neural differences for each MI among ability groups.

The fourth investigation addressed the question, are there intrinsic, resting-state functionally connected (rsFC) neural networks related to each of the multiple intelligences? This study of 48 rsFC studies found seven to fifteen neural networks that are clearly aligned with each of the multiple intelligences and with general intelligence. Twelve whole brain, model-free rsFC investigations revealed 13 neural networks that are closely associated with seven of the eight intelligences. These data were supported by 35 region-of-interest, model-dependent studies that also identified 20 sub-networks associated with multiple intelligences and specific skills. These data indicate that the neural regions with cognitive correlates associated with the eight intelligences form coherent units.

The fifth investigation (1) compared the neural architectures cited for general intelligence with a proposed new category of Cognitive Qualities associated with the multiple intelligences. This investigation of 94 neuroscientific studies found neural support for the coherence of a new category of Cognitive Qualities as distinct from the convergent problem-solving of IQ. A similar neural pattern was evidenced among the three Cognitive Qualities that are valued abilities integral to the definition and practical expression of each of the eight intelligences.

The validity of any new idea can be difficult to establish and this is especially so for a theory of intelligence that challenges prevailing ideas and does not lend itself to psychometric testing. Fortunately, the field of neuroscience provides a wealth of experimental data that aligns well with the MI definition and the cognitive components for the various intelligences. Taken together the investigations described above indicate that the multiple intelligences have clear, logical, and coherent neural patterns that are comparable to those identified with general intelligence. These data lend support to the proposition that each of the eight intelligences have unique neural architectures and that the idea of general intelligence is not incompatible with MI theory.

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