DISSERTATION

RELATIONSHIPS AMONG SPEED OF PROCESSING, APTITUDE, AND WORKING MEMORY IN ELEMENTARY STUDENTS

Submitted by

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ABSTRACT

RELATIONSHIPS AMONG SPEED OF PROCESSING, APTITUDE, AND WORKING MEMORY IN ELEMENTARY STUDENTS

This research explores the relationships between speed of processing, verbal and quantitative aptitude, and working memory for elementary age students. Students with impaired processing speed often struggle in elementary school and can be incorrectly identified as lazy or unintelligent. This can have lasting consequences on their self-esteem and future academic success. The findings of this research suggest that the combination of processing speed, working memory and academic achievement in reading does not adequately predict verbal intelligence. However, the model indicates that there is a relationship between the variables of processing speed, working memory, and mathematic achievement to predict quantitative intelligence. Additionally, there was no statistically significant correlation of processing speed and verbal aptitude for this sample. Likewise, there was no statistically significant correlation of speed of processing and quantitative aptitude. The research shows a statistically significant difference between processing speed and academic achievement in reading and in mathematics; reading and speed of processing, as well as mathematics and speed of processing. Ultimately, this research suggests that students with impaired processing speed do not demonstrate impaired aptitude in reading or mathematics. However, this research also suggests they may struggle with academic achievement in both reading and mathematics. This gap between aptitude and achievement is an important characteristic to remediate so that students with lower processing speeds can be successful in school.

Keywords: processing speed, working memory, cognitive capacity, academic achievement

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CHAPTER I: INTRODUCTION

Statement of the Research Problem

Academic achievement in mathematics and reading are often cited as teachers' top priority for their students (O'Connor, 2008). After all, teachers are generally drawn to their career because they care deeply about helping students learn and reach their maximum potential (Hall, 2006).

Another issue equally important to elementary teachers is their students' emotional well-being (Hamre & Robert, 2005). Teachers have an intimate understanding of the relational aspects of teaching and learning; teachers understand and bear witness to the fact, that in the absence of engagement and enjoyment, young students are not likely to learn much at all (Hamre & Robert). In fact, when students are uncomfortable and unhappy at school, it can have long lasting and potentially devastating consequences. Many studies clearly indicate a significant and persistent relationship between students' self-esteem and their academic achievement (Combs & Soper, 1957; Daniel & King, 1995; Farquhar, 1968; Friedland, 1992; Irwin, 1967; Purkey, 1970; State of California, 1990). In essence, these studies all indicate students who feel confident about their abilities are more likely to succeed, and those who do not are more likely to fail.

Students who process more slowly than their peers often struggle to achieve the academic success they deserve, and consequently, they suffer emotionally as well (Hall, 2006). Some are quick to judge these students; slow processing students are often regarded as lazy daydreamers who are careless and unmotivated (Hall, 2006). Worse yet, these students are sometimes dismissed as stupid and unable to learn (Daniel & King, 1995; Friedland, 1992). This is an unacceptable conclusion. When students with slow processing speeds are asked to perform at a tempo that does not match their own natural rhythm, they demonstrate a discrepancy between their performance and their capacity. In crass vernacular, they appear stupid. This, in turn, makes students feel embarrassed, ashamed and heartbroken – certainly not the ingredients needed for academic success. Students who believe (or who have been told) they are stupid do not feel confident about their abilities, and do not feel good about themselves (Hall, 2006). This is the reason this research is important: educators need a deeper understanding of students with diminished speed of processing capabilities.

Purpose

The purpose of this study is to explore the research about intelligence and its relationship to speed of processing, working memory, and academic achievement. This research will analyze the assessment results for a sample of students who have been identified by a teacher as needing additional support. By exploring the cognitive and academic profile of students with diminished speed of processing, this research will provide a better understanding of what it means to be a slow processor; more is illustrated about the strengths and weaknesses of students who process slowly. I hope to capitalize on the strengths, and mitigate the weaknesses for students with diminished processing speed. I hope to convince other practitioners that we do not need erroneous labels but rather we need to help all of our students reach their full potential. Simply put, the research hopes to find evidence that the students who process more slowly than their peers are not "lazy" and may simply need more time to demonstrate their knowledge.

Theoretical Framework

The theoretical framework for this study is pragmatism. I have started this research believing the nature of knowledge, language, concepts, meaning, belief and science are best viewed in terms of their practical uses and successes. As Dewey believed, I also think that we must have a conception of education that views learning not as a means to an end, not as a preparation for life, but as life itself (Dewey 2004; Dewey 1997, p. 47). The pragmatic paradigm stresses action, which is precisely what I am interested in. I seek to explore how students with diminished speed of processing learn and perform and what their strengths and weaknesses are so that we, as practitioners, can take action to help them be more successful in school.

Pragmatism aligns well with my research in that it allows me to focus on the 'what' and 'how' of my research problem (Creswell, 2003). *What* are the strengths and weaknesses of students who have impaired processing? This information can inform h*ow* educators can improve our instruction to meet the needs of these students. The pragmatic paradigm places the research problem as essential and applies all approaches to understanding the problem (Creswell, 2003, p.11). Furthermore, pragmatism is considered to be problem-centered and real-world practice oriented, concerned about the consequences of our actions and interested in meaningful and practical solutions. I am most interested in the practical solutions educators can use to help students be happy and successful at school.

Research Questions and Hypotheses

My hypothesis is that students with slower processing speeds are as bright and as capable as their peers are, but they simply need more time. Some research indicates that they need time to think before they respond, they need time to ponder before coming to a conclusion, and they need time to comprehend what they are reading, but this need for additional time does not mean that they are not capable (Catts, Gillispie, Leonard, Kail, & Miller, 2002; Hamre & Robert, 2005).

To understand and learn more about the cognitive profile of slow processing students, I will attempt to answer the following research questions:

- RQ1.) How well can I predict students' aptitude scores (CogAT) from a combination of three variables: MAP, CToPP rapid naming and CToPP working memory?
    - How well can I predict students' verbal aptitude scores (CogAT Verbal) from a combination of MAP reading, CToPP rapid naming and CToPP working memory scores?
    - How well can I predict students' quantitative aptitude scores (CogAT Quantitative) from a combination of MAP math, CToPP rapid naming and CToPP working memory scores?
- RQ2.) What is the strength of the correlation between speed of processing and aptitude in verbal and quantitative reasoning?
- RQ3.) What is the strength of the correlation between speed of processing and academic achievement in reading and mathematics?
- RQ4.) Is there a difference in aptitude and academic achievement between the four cohorts?
    - Low speed of processing only?
    - Low working memory only?
    - Double deficit (low processing speed and low working memory)?
    - No deficit?
- RQ5.) What is the strength of the correlation between speed of processing, working memory, aptitude, and academic achievement for each individual cohort?
    - Low speed of processing only?
    - Low working memory only?

- Double deficit (low processing speed and low working memory)?
- No deficit?

Relevant Terminology

Throughout this study, the following terms are used:

1. **CToPP** – Comprehensive Test of Phonological Processing. An individually administered test used to determine students' speed of processing, working memory capacity, and phonemic awareness (Wagner, Torgesen, & Rashotte, 1999).
2. **MAP** – Measures of Academic Progress. An adaptive, computer-based assessment, used to determine reading and mathematics achievement for students throughout the United States (Northwest Evaluation Association, 2012).
3. **CogAT** – Cognitive Abilities Test. Used to determine aptitude in verbal, non-verbal/spatial, and quantitative reasoning (Lohman, Cognitive Abilities Test: Research and Development Guide, 2012).
4. **Cognitive Capacity** – a proxy for intelligence or IQ. Determined by the results of the CogAT for this study. Synonymous with aptitude (Lohman, Cognitive Abilities Test: Research and Development Guide, 2012).
5. **Speed of Processing** – the speed at which an individual can complete basic cognitive functions such as naming or discriminating between familiar items (Fry & Hale, 2000). Measured by the results of the CToPP Rapid Naming tests.
6. **Working Memory** – the active part of the memory system; information is simultaneously processed and stored for use at some time in the near future. Working memory allows individuals to keep information in mind while also using it to

complete a task (Alloway, 2011). Measured by the CToPP Memory tests for this study.

Delimitations

This study faces several delimitations, which will certainly influence the generalizability of my findings. I examined a small sample (n=72) of students from one elementary school with limited diversity. Each of the students was assessed in 2nd or 3rd grade, and their homeroom teachers referred students to me. The consequence of these delimitations is that my study will not be generalizable beyond my specific elementary school. However, because I am a practitioner at the school where my sample population attends, I do believe I can draw conclusions that will influence the work of my colleagues and students, and spur action to improve learning throughout my school.

Researcher's Perspective

Without question, I enter this study with bias. I love my students and have a personal relationship with them. Their future matters to me. My hypothesis claiming students with diminished processing speed are as intelligent and capable as their peers is based on relational elements, and may not take into consideration students' true capacity. I freely admit I want these students to be smart and capable!

As an elementary school educator, providing high-quality learning experiences for each of my students is a priority; it is simultaneously an imperative and a challenge. Most of the students with whom I have the pleasure of working arrive at school well-equipped to learn and participate. They are eager to learn, to socialize, and to contribute to the learning community. Others, however, join us with a different set of attributes. Some have learning or emotional disabilities that can impede their experience at school. Others come from home environments in which their fundamental needs are not always met adequately.

One group of students, in particular, has held my interest for the last several years—students with below average speed of processing capabilities. Nine years ago, I had the privilege of moving from my second-grade classroom into an Intervention and Assessment Coordinator role. This position affords me the opportunity to work specifically with students who are performing below grade level. My responsibilities also include administering diagnostic assessments to students referred to me by their teachers. Most of the students I test have fundamental gaps in their knowledge, particularly in their phonemic awareness or phonics skills, but some have issues that are not as easy to decipher. These students often know the phonics rules, can hear and manipulate sounds just fine, and can communicate effectively, if not efficiently. Their reading skills are fair, as are their mathematic skills. However, they are the students who struggle profoundly to finish their work in a timely way. Often, homework can take hours to complete. They grow weary by the end of the school day, and often grow to dislike school as the years progress. Their teachers are weary, too, because the interventions that often work to motivate and engage students do not seem to work on these children.

The ability to process information and respond efficiently (speed of processing) is a skill that is artificially accentuated in elementary school (Catts, Gillispie, Leonard, Kail, & Miller, 2002). Students are on a Henry Ford-like assembly line of curriculum and assessment, and there are few, if any, opportunities to stop the conveyor belt. Students with speed of processing deficiencies are at an enormous disadvantage (Daniel & King, 1995). In my experience, these students need additional time to think before producing. They need time to process before answering, and they need time to ponder before they can take any academic risks. When sitting on the conveyor belt, time is scarce; students just have to keep moving or they fall off on to the floor. This causes embarrassment, and ultimately, resentment about going to school (Daniel & King, 1995).

Students with speed of processing deficiencies confuse some teachers. My colleagues often describe these students similarly, saying they are not motivated, they are lazy, or they are not meeting their potential. Many teachers seem to think students with speed of processing deficiencies fall into one of two categories: not willing to work hard, or not able to do the work (Hall, 2006). I have long felt these students are none of the above; they are not lazy and are doing their best to keep up with their peers. They seem to try to blend in, looking "busy" even if the work they are doing is inaccurate or different from what the teacher has asked the students to do. I believe these children are extremely capable and intelligent, and given the right environment and circumstances, they can excel. However, educators may need to adjust their instructional approaches and paradigms about intelligence in order to make that happen.

The goal of my research is to inform teachers of the cognitive profile of the students with diminished speed of processing. Knowing whether a child's speed of processing is indicative of his or her capability can dramatically change the way a teacher approaches a student. In other words, do students with below average speed of processing skills also have below average cognitive capacity? Do these students demonstrate below average performance on standardized academic achievement tests for reading and math? Can we predict a student's aptitude or achievement based on their speed of processing? I will investigate, empirically, how these students perform on both aptitude and achievement tests. My hope is this investigation will help me learn about the cognitive aptitude of students with speed of processing deficiencies, which will inform how we might help make their elementary school experience more successful. I hold strong to the belief that my students learn the most when they are happy, and it seems that all too often, my students with diminished speed of processing are not happy at all.

If my hypothesis is correct, I will have evidence that many slow processing students are as intelligent and capable as their peers. If my hypothesis is wrong, I will have evidence of the weaknesses these students face. Regardless of the results, I believe there is an enormous potential to inform the teaching practices in my school. With this information, my colleagues and I can examine our pedagogy, consider alternatives, and hopefully prevent these students from feeling like, and hence potentially becoming, academic failures.

Assumptions and Limitations

Teachers who have a concern about a student's performance in class often ask me to provide additional assessments to help explain how they may help that child. When teachers request it, I administer the CToPP as a diagnostic tool. The limiting factor is that all the students in my sample have raised a concern for their teacher regarding their academic performance. Therefore, even the students in my sample who did not demonstrate any processing deficiencies are not necessarily "typical peers." Because each of the assessments I used have been nationally normed, I hope to abate some of this limitation. In other words, the students in the sample who perform in the average range on the CToPP, CogAT or MAP assessments are "average" compared to students nationwide, not "average" for my school specifically. Even so, my small and unusually determined sample may affect the results of this study.

CHAPTER II: REVIEW OF THE LITERATURE

Introduction

There is extensive and contradictory literature about the relationship between processing speed, memory, and intelligence in children. Certainly, there are no clear answers to the questions regarding what intelligence is including how it is best measured or if it is consistently correlated to speed of processing or working memory. This literature review contains general definitions followed by an examination of the relationship between processing speed, intelligence, academic achievement, and memory. In addition, I study the apparent contradictions in the empirical literature about the correlation between speed of processing and intelligence. Finally, literature regarding the interactions between speed of processing, intelligence, working memory, and academic achievement in reading and mathematics are explored.

Intelligence

The definitions available for intelligence are varied and debatable. Some argue the word intelligence is not a scientifically useful term in that “it has no generally agreed upon meaning, and psychologists seem hopelessly unable to achieve a consensus on what this term should mean” (Jensen, 1993, p. 123). This argument has no clear conclusion.

Types of Intelligence

Some argue there are many different “intelligences” or systems of abilities, “only a few of which can be captured by standard psychometric tests” (Gardner, 1999, p. 203). It is important to consider while many studies claim to focus on general or fluid intelligence, it is possible the psychometric tests used to evaluate the sample could, in fact, be measuring a different intelligence altogether.

For instance, Gardner's (1999) theory proposed there are several distinct and specific forms of intelligence: musical intelligence, bodily-kinesthetic, personal intelligence, linguistic, logical-mathematical and spatial. One could argue these are talents rather than intelligences, but he offered compelling evidence to suggest that different individuals have capacities in different arenas (Intelligence reframed: multiple intelligences for the 21st century, 1999).

Sternberg (1985) proposed there are three fundamental aspects of intelligence: analytic, creative, and practical. He argued only analytic intelligence is measured to any significant extent by mainstream tests, and one piece cannot encapsulate the true nature of a person's understanding and knowledge. Furthermore, he placed a specific value on *tacit knowledge*, which he defined as the type of practical knowledge that one acquires without any direct help from others and that allows individuals to reach goals they personally value (Sternberg, 1985). Although Sternberg's theories have been sharply criticized (Jensen, 1993), there does seem to be a distinction between analytic and practical intelligence (American Psychological Assicoation, Inc., 1996, p. 79). For instance, a child living in poverty may have a great deal of knowledge about where a family may be able to get a warm meal and free shower (practical intelligence) but little ability to solve algebraic mathematics problems (analytic intelligence) while a privileged child would have no knowledge of the former and some experience with the latter.

Prior to Sternberg (1985) and Gardner (1999), Piaget (1977) proposed intelligence develops in all children through the continually shifting balance between "the assimilation of new information into existing cognitive structures and the accommodation of those structures themselves to the new information" (American Psychological Assicoation, Inc., 1996, p. 81). Thus, intelligence can never be accurately measured outside a single moment in time. Researchers also often reference Vygotsky (1930-1934/1978), who argued all intellectual abilities are social in origin and that our capacity should be measured by what we can do *alone* as well as what we can do *with scaffolding*, or what Vygotsky called the Zone of Proximal Development (American Psychological Assicoation, Inc., 1996, p. 81). Traditional intelligence tests ignore a child's Zone of Proximal Development, simply measuring static intelligence rather than potential.

These distinctions are important to note because one must be clear about what is being measured. While several studies (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Demetriou, Spanoudis, Shayer, Mouyi, Kazi & Platsidou, 2013; Fry & Hale, 1996, 2000; Geary, Brown, & Samaranayake, 1991; Kail, 2000; Martinez & Colom, 2009) make grand claims about correlations between certain variables and intelligence, the means of measuring intelligence are varied. Although these researchers claim to have found meaningful relationships between intelligence and several other attributes, it is at least possible that they were not measuring the same "type" of intelligence.

Fluid intelligence.

Fluid intelligence is different from acquired knowledge, or crystallized intelligence, and is meant to be synonymous with reasoning ability (Fry & Hale, 2000, p. 9). Therefore, it is a dynamic rather than static property of human functioning and can be affected by "a number of maturational and experiential forces" (Fry & Hale, 2000, p. 9). Fluid intelligence is defined as:

> …the expression of the level of complexity of relationships that an individual can perceive and act upon when he does not have recourse to answers to such complex issues already stored in memory. Determined by tests with little cultural content – abstract tests that depend on figuring out the relationships between certain words when the meanings of all the words themselves are highly familiar. (Martinez & Colom, 2009, p. 282)

Processing Speed

Perhaps only slightly less controversial than the definition of intelligence is the definition of processing speed. Many researchers have argued processing speed accounts for the relationship between working memory capacity (defined below) and fluid intelligence. Processing speed is considered a key characteristic of intellectual capacity (Sheppard & Vernon, 2008). Processing involves taking in new ideas, transforming and synthesizing thoughts around those ideas, and retrieving information about how we communicate those ideas. This act of processing takes time. Therefore, processing information quickly allows a greater volume of information to be managed in a given amount of time without that information leaving our working memory before we can make sense of the input (Jensen, 1993; Kail & Salthouse, 1994; Salthouse, 1996). The loss of information during processing is called decay and will be discussed at greater length below.

Fry and Hale (2000) offer a clear definition of processing speed: "the speed at which an individual can complete basic cognitive functions such as naming or discriminating between familiar items" (p. 8). While this definition does not include details about the interaction of processing speed with memory, it provides a clear explanation of the construct. Throughout this study, processing speed indicates the speed at which an individual can encode, transform or retrieve information.

One method to determine an individual's processing speed is though rapid automatized naming (RAN). Individuals are asked to name, as quickly as possible, a series of items. Most commonly, RAN assessments use a combination of letter, number, object and/or color identification. The efficiency by which a person can quickly identify and then say the name of the item is a measure of that person's processing speed. RAN has been placed within the phonological processing domain, along with phonological awareness (both synthesis and analysis) and memory (both memory span and working memory) (Denckla & Cutting, 1999, p. 33). Phonological processing is the ability to hear the discrete sounds within a word and then associate those sounds with the letter or letters that make up that word. Phonological processing is a critical component of efficient reading and writing (Denckla & Cutting, 1999; Fry & Hale, 2000; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007) and current research indicates it may also be crucial to efficient mathematics understanding and computation (Hecht, Torgesen, Wagner, & Rashotte, 2001).

According to Denckla and Cutting (1999), rapid automatized naming can, "in large part, be accounted for by processing speed" (p. 34) but cannot be fully explained by it. Therefore, whatever RAN represents, it is in part included under the domain of processing speed. Kail (2000) agrees, but goes even further, stating RAN performance represents generalized processing speed. This argument stems from research that shows RAN performance and reading achievement are highly correlated; Kail and Powell, et al. propose that the explanation for this relationship is the same underlying factor – processing speed (Kail, 2000; Powell, et al.). Therefore, by measuring RAN, you are measuring processing speed (Powell, et al.).

Working Memory

In 1974, Alan Baddley and Graham Hitch proposed a model of working memory that expanded upon the common thinking about short-term memory. At the time, short-term memory was considered a single store mechanism, and it was widely held that all information went to this mental system and was processed in the same way. Baddley and Hitch (1974) felt this was an overly simplistic model, believing there are multiple systems for differing types of information (verbal, written, numeric, etc.), rather than one single storage space. They created a model for working memory/short term memory that included three components: the central executive system, the phonological loop and the visuo-spatial sketchpad (Baddeley & Hitch, 1974). See Figure 1 (below) for a visual representation.

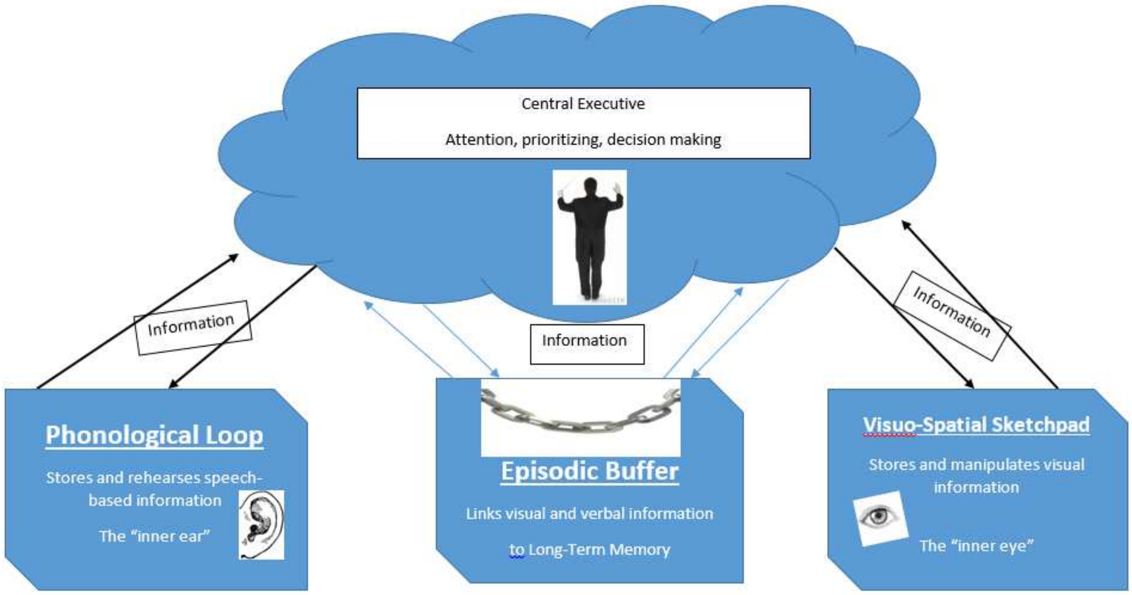


Figure 1: Working memory model.

Central Executive System

In Figure 1, the central executive system serves as a conductor to the phonological loop (inner ear) the Visuo-Spatial Sketchpad (inner eye) and the episodic buffer. This conductor is responsible for directing attention, determining immediate priorities and facilitating rapid decision-making (Baddley & Hitch, 1974; Baddley, 2000). In this model, the central executive system is the attention control, or the conductor of the other two sub systems. The central executive system is responsible for allocating inputs and data to the visuo-spatial sketch pad or the phonological loop as well as deciding what to attend to, focus on, and also what to ignore or tune-out. For example, when doing two things at once, such as driving a car and talking on the phone, one activity may demand our direct attention. If the cars in the front of a line of traffic stop suddenly, the driver will drop the phone and focus on breaking to avoid an accident. The central executive system prioritizes our attention, and in this example, makes the decision to operate the car. Rather than serving as a system of memory storage, Baddeley suggests that the central executive controls attention; it allows the working memory to pay attention to certain inputs while ignoring others.

Baddeley (1986) uses the metaphor of an industry supervisor to explain the role of the central executive system. The supervisor is responsible for making decisions about what needs to be done, what is the biggest priority and what should be disregarded. The supervisor is also responsible for solving problems, but can only do one or two things at the same time. In order to find solutions, the supervisor or boss will collect inputs from many different resources. As Baddeley (1986) explained, the central executive system combines information from the two sub-systems of phonological loop and visuo-spatial sketchpad and also gathers input from long-term memory to solve problems. (Baddeley, A. D., 1986)

The phonological loop is essentially the verbal short-term memory and addresses written and spoken information. It is broken into two parts: the phonological store and the articulatory control process. The phonological store serves as what Baddeley referred to as an inner ear, and holds spoken information for 1-2 seconds at a time. He explained that spoken words enter the store directly while written material must be changed into an articulatory code before entering the phonological store. In other words, written words become the voice we hear while we are reading. Meanwhile, the articulatory control process serves as an inner voice and is linked to speech production. This process rehearses the information from the phonological store – imagine saying a phone number you need to remember as you walk over to the telephone. Repeating the numbers over and over helps to keep the information in working memory. Baddeley also believes the articulatory control process changes written material into a verbalized code (the inner voice) which is then transferred to the phonological store (Baddeley & Hitch, 1974).

Visuo-Spatial Sketchpad

The second sub-system of the working memory is what Baddeley and Hitch (1974) called the visuo-spatial sketchpad. This system is often called the inner eye, and encodes visual and spatial information processing. Baddeley (1997) explains the visuo-spatial sketchpad helps us remember what things look like, and plays a critical role in helping us understand where our body is in space as we navigate through our environment. This system also allows us to "see" visual and spatial information held in long-term memory. For instance, if you are planning to drive to work, but need to stop and get gas on the way, you might picture the drive and see the gas station in your mind. This picture has been retrieved from long-term memory and is now on your visuo-spatial sketchpad (Baddeley, 1986).

Evidence presented in the original 1974 model suggested working memory uses a different system for processing visual information than for verbal information. Specifically, Baddeley and Hitch (1974) found that it is possible for a person to perform a visual processing task and a verbal processing task at the same time, but it is significantly more difficult to perform two visual processing tasks simultaneously—the tasks create interference with one another. The same interference occurs when trying to perform two verbal tasks simultaneously. This evidence supported the model that the phonological loop and the visuo-spatial sketchpad are independent and separate systems within working memory (Baddeley & Hitch, 1974).

Episodic Buffer

In 2000, Baddeley updated his working memory model after the old model failed to explain the results of various experiments. Baddeley added a system he called the episodic buffer. This system is responsible for communication between long-term memory and working memory. The episodic buffer acts as a 'backup' store that communicates with both long-term memory and the components of working memory. His updated model is a shift of focus from examination of the isolated subsystems to a focus on the processes of integrating information. Baddeley (2000) was motivated to include this fourth piece to the model due in part to his observation that several extremely intelligent patients with amnesia had good short-term recall of stories, but lacked the ability to add new information to their long-term memory. These patients could remember stories, and recall more information than could reasonably be held in the phonological loop. This indicated there was “evidence of a temporary store that is capable of holding complex information, manipulating it and utilizing it over a time scale far beyond the assumed capacity of the slave systems of Working Memory” (p. 419).

Working memory is the active part of the memory system; information is simultaneously processed and stored for use at some time in the near future (Alloway, 2011). Working memory allows individuals to keep information in mind while also using it to complete a task (Alloway, 2011). It is similar to the more traditional concept of short-term memory, but is more complex. As explained above, working memory is generally believed to be controlled by a central executive system within the brain that simultaneously demands verbal information processing and visuo-spatial information processing (Fry & Hale, 2000, p. 8). In other words, our working memory allows us to hold information that we see or hear for short periods while completing or executing a different task that uses that information.

If working memory is a mental desktop, a good example of a time we use working memory would be solving a mathematics problem without the use of paper and pencil. Our working memory stores information while we simultaneously process other thoughts or ideas. If students were asked to multiply 42 and 25 together, they would need to hold those two numbers in their working memory. The students would also need to recall multiplication rules, complete computations, and then add the new numbers to their working memory. After that, the students would add the products (that were held in working memory) and arrive at the correct answer. Poor working memory capacity makes this sort of complex thinking extremely difficult, if not impossible; working memory makes it possible to keep information in mind while processing other information.

Increases in working memory allow individuals to "represent and process more information units at the same time" and as a result they can "construct more complex concepts or relations" (Demetriou, et al., 2013, p. 35). The maximum amount of information that can be retained during short periods of time significantly contributes to an individual's reasoning and problem solving ability (Martinez & Colom, 2009). However, processing speed can limit an individual's working memory capacity because processing information takes time. Fast processing speed can increase the amount of information that can be managed in a given amount of time, but if an individual's working memory is poor, the speed at which the information is processed is moot, as that information does not "stick" and cannot be used to execute a task. This dropping-off of information is referred to as information decay (Martinez & Colom, 2009).

The Relationship Between Intelligence, Processing Speed, and Memory

Throughout the literature, claims of correlation between speed of processing and intelligence are presented, but in each instance, those claims are ultimately tempered with caveats. For example, the American Psychological Association states, "there are significant correlations between measures of information-processing speed and psychometric intelligence, but the overall pattern of these findings yields no easy theoretical interpretation" (American

Psychological Assicoation, Inc., 1996, p. 97). Fry and Hale (2000) conducted a large analysis of the literature and discovered that "it is well established that processing speed and intelligence test scores are correlated, although the strength of this relationship is still a matter of debate" (p. 2).

Processing speed and the capacity of working memory have been offered as key cognitive functions for intelligence (Martinez & Colom, 2009; Sheppard & Vernon, 2008). Sheppard and Vernon (2008), who conducted a review of 50 years of research, found "the overall correlation between mental speed and intelligence is moderate but very consistent across all the different studies and measures that were reviewed" (p. 542). However, they go on to explain "individual differences in any single measure of speed of information-processing by no means accounts for a substantial amount of the variance in intelligence" (Sheppard & Vernon, 2008, p. 542). It seems there is a connection between speed of processing and intelligence, but our understanding of the connection is muddy, at best.

Despite the minimal understanding of the relationship, there is a consistent and strong link between speed of processing and working memory. Jensen discusses the link between processing speed and memory by explaining the importance of speed:

> Speed is important because of the brain's limited capacity for processing information. Although there may be multiple independent processing resources, when one's attention is highly focused, as in solving a complex and novel problem that cannot be handled by automatized skills, there is a bottleneck in channel capacity. Also, information coming into the central processing unit (often called working memory) from external stimuli or from long-term memory is lost rapidly. If all the information that is needed to solve a problem is not processed before it is lost, it must be taken in again by repetition of the stimulus or repeated retrieval from long-term memory. Hence, achieving a correct or adequate solution is a race between two variables: speed of processing and rate of decay, or loss, of the information needed. Thus, persons with faster speed of processing have faster response times on elementary cognitive tasks than persons with slower processing speed, and can also acquire knowledge and skills faster, retrieve information from long term memory more efficiently, reason better, and solve more complex problems on mental tests. (Jensen, 1993, p. 54)

Essentially, Jensen is suggesting that if an individual processes slowly, there is increased potential for incorrect responses, poor reasoning and less overall knowledge acquisition.

This may help explain why, in nearly every article, it was difficult to parse out the speed question from the memory question. Additionally, “processing speed, memory, and reasoning all improve with age, raising the possibility that these changes are not independent, but related” (Kail, 2000, p. 57). Fry and Hale (1996) proposed a strong form of interdependence, which they called developmental cascade, finding as children age, their “processing speed becomes faster, leading to improvements in working memory, and improved working memory, in turn leads to increases in [reasoning and problem solving]” (p. 237). This is relevant because “as children process information more rapidly, they can use working memory more effectively, which allows them to solve problems like those on the test of fluid intelligence more successfully” (Kail, 2000, p. 58). This begs the question, however, is it the speed of processing that is improving fluid intelligence or is it working memory that is at play?

Kail (2000) attempts to answer this question, explaining rapid/efficient processing enhances memory, which, in turn, enhances reasoning. Additionally, he states processing speed can influence intelligence test results both directly and indirectly. An indirect effect is illustrated by the impact of processing speed on memory. By allowing working memory to be used more efficiently, increased processing speed enhances performance on intelligence tests indirectly. However, “processing speed may also affect performance directly by speeding up retrieval of task-relevant information from long-term memory” (Kail, 2000, p. 58).

Using this reasoning, it is easy to see the “cascade effect” that Fry and Hale (1996, 2000) refer to—one piece leads to the next, which leads to the next, as so on. This explanation makes sense and is consistent with findings throughout much of the literature.

In the Kail (2000) report, all results are based on the fact that the cascade effect has been evidenced "many times in studies of individuals with mental retardation: On most tasks which required rapid responding, individuals with mental retardation respond more slowly than individuals without mental retardation" (Kail, 2000, p. 57). Although these results are based on a unique population, they do present evidence that memory and speed of processing are intricately connected, even though processing speed is less directly correlated to intelligence. "Processing speed is not simply one of many different independent factors that contribute to intelligence; instead, processing speed is thought to be linked causally to other elements of intelligence" (Kail, 2000, p. 58) which complicates the relationship between intelligence and processing speed.

Throughout the literature, evidence is presented that demonstrates statistically significant relationships between fluid intelligence, short-term memory, working memory and processing speed. The results suggest "working memory capacity, but not short-term memory capacity or processing speed, is a good predictor of general fluid intelligence" according to Conway, et al. (2002, p. 163). Working memory capacity is, in their view, the primary contributing factor to predicting intelligence. This stands in contrast to the conclusions drawn by other researchers. The goal of the Conway et al. (2002) study was to "explore the four-way relationship between working memory capacity, short-term memory capacity, processing speed and fluid intelligence" (p. 164). By trying to "identify the primary contributor to individual differences in fluid intelligence" (2002, p. 165), they attempted to mediate the conflict between theorists who speculate that processing speed, working memory capacity, short-term memory capacity or some combination therein serves as the primary predictor of fluid intelligence.

Jensen disagrees with the idea that working memory capacity is the primary contributor to fluid intelligence, and he states repeatedly that the *interplay* between processing speed and working memory capacity is responsible for an individual's fluid intelligence; working memory is not more important than processing speed (Jensen, 1993). In fact, he goes so far as to state that speed of processing is the "purest manifestation" of fluid intelligence because it reflects the "quality of information processing in the brain" (Demetriou, et al., 2013, p. 35). Despite the essential agreement that working memory and processing speed both contribute to fluid intelligence, there is still wide debate and conflicting findings about which factor is the most important component or contributor to intelligence. These results are decidedly different from what was found in this research, see chapter four.

The Conway et al. (2002) study suggested that when measuring processing speed with tools that "place minimal demands on memory and attention," (p. 178) processing speed does not significantly predict fluid intelligence. This stands in contrast to the abundant literature connecting fluid intelligence and speed of processing (Catts, Gillispie, Leonard, Kail, & Miller, 2002; Jensen, 1993; Kail, 2000). Conway et al. (2002) explained this difference by offering that the prior studies did not consider the working memory demands of the speed tasks used (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002, p. 178). "One finding that clearly emerges from the literature is that the more "complex" the speed task, the stronger the relationship is between speed and intelligence" (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002, p. 180). In other words, when students are asked to complete speed tasks that tax memory and attention, processing speed and fluid intelligence become correlated. "Thus, it is not speed per se that predicts fluid abilities" (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002, p. 180). Task complexity must be accounted for. When the tasks become complex, working memory capacity is essential to remembering the information that is being processed before that information decays. These results better match with this research's finding; see chapter four.

This leads to additional concerns about the measurement tools and practices involved in prior studies. Speed of processing was measured in various ways throughout the studies referenced above. Shepperd and Vernon (2008) found that the studies they cited categorized mental speed measures as "reaction time, general speed of processing, speed of short-term memory processing, speed of long-term memory retrieval, or inspection time" (p. 537). Only two of the studies cited used rapid automatized naming (RAN) as a measure of processing speed. As I will discuss further in Chapter 3, RAN is the instrument used to determine speed of processing for this study.

Another measurement concern noted by Fry and Hale (2000) is that nearly all the studies in this area used multiple age groups and "have not taken the consequences of age-related changes in speed into account" (p. 11). This also may have skewed the results regarding the relationship between speed and fluid intelligence. Additionally, they found that the correlations varied, depending on "the methods of measuring response time and intelligence, the reliabilities of these measures, and the population under study" (Fry & Hale, 2000, p. 12).

Fry and Hale (2000) also found that many of the studies they examined used a Jensen apparatus to determine response time, in which longer response time equates to slower speed of processing. This device "consists of a 'home button' and eight lights, each of which has a corresponding response button. The number of choice alternatives is varied by changing the number of lights that are used" (2000, p. 13). In their own study, Fry and Hale (1996) derived an overall speed score by averaging across four different speed tasks, none of which included RAN.

According to Conway et al. (2002), "because they aggregated across tasks that in our view tap different abilities, the predictive validity of processing speed is indeterminate" (p. 167). This could mean that the Fry and Hale (1996) study may be misleading, attributing more predictive power to processing speed than it actually has.

As previously mentioned, the Conway et al. study had unique results in that there was *not* a demonstrable relationship between processing speed and fluid intelligence, "a result that stands in stark contrast to a large literature on the relationship between speed and fluid intelligence" (2002, p. 180). The study also did not include RAN as a measure of processing speed. Three of the four speed tasks were completed using a computerized program and one was completed with paper and pencil. Unlike RAN tasks, students did not have to answer anything aloud. While their results were different from most, it is important to note that evidence was presented to demonstrate that it was not the case that the speed measures were unreliable or lacked variability. The measures were reliable and demonstrated contributing covariation, but they were not covarying with the intelligence measures (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002, p. 177).

In an analysis of three empirical studies, covering an age span of 4-16 years, Demetriou, et al. (2013) determined a "more refined" (p. 46) theory for predicting intelligence was needed, beyond attributing the majority of contribution to only processing speed or working memory capacity. Specifically, they claimed that fluid intelligence increases with age because children learn that they must self-regulate the speed of their performance based on the processing requirements of the task at hand (Demetriou, et al., 2013, p. 47). In other words, children learn that in certain situations, going too fast can lead to incorrect responses, while going too slow can impede problem solving (due to informational decay.) Additionally, change in any one process, such as speed, “is functionally necessary for change in another process, such as working memory or fluid intelligence” (Demetriou, et al., 2013, p. 48). This provides further evidence of the intricate relationship between processing speed, working memory and intelligence, and may enhance argument for the cascade effect proposed by Fry & Hale (2000).

From the meta-analysis conducted by Fry & Hale (2000), three issues related to the relationship between processing speed, working memory and intelligence emerged. The first issue was an examination of the “the time course of developmental increases in cognitive ability” (p. 29). The second issue examined how age influences individual differences in speed, working memory and intelligence. The third issue explored the “mechanisms by which developmental increases in different aspects of cognition affect each other” (p. 29).

Studies in which processing speed, working memory and fluid intelligence were measured as a function of age have “almost universally found relatively precise nonlinear growth functions” (Fry & Hale, 2000, p. 29). In other words, when researchers tried to use age to predict working memory, speed or intelligence, the results followed very similar and predictable paths. Each of the functions had essentially the same form but also provided strong evidence that all three variables develop “in concert” (p.29). We can expect processing speed, working memory and intelligence to improve with age in a predictable nonlinear way, hitting a ceiling near the end of adolescence.

Fry & Hale (2000) found in studies of the relationship between speed and fluid intelligence among individuals who were all the same age, the correlations had wide variation depending on the method used to measure processing speed and intelligence, as well as the population being studied (students with a cognitive disability or not). Even though there was a great deal of variability, the correlations were almost always negative. In other words, those who took less time to respond demonstrated higher fluid intelligence; more intelligent individuals tended to take less time to respond. However, the strength of the relationship between individuals' speed and intelligence "does not appear to change systematically during childhood" (Fry & Hale, 2000, p. 12). This is important because it is contrary to what would be expected based on the current understanding of the development of processing speed in children, referenced above. Children approach a physiological ceiling in processing speed as they grow older, and therefore one would expect to observe a decrease in speed variability and a "resulting reduction in the possible correlation within an age group as they approach adulthood" (Fry & Hale, 2000, p. 12). Ultimately, there is little evidence of "systematic change in the strength of the correlation between speed and intelligence with age" (Fry & Hale, p. 29). Unfortunately, very few studies have been conducted using samples of same age children to examine the correlations between processing speed and working memory or between working memory and intelligence (Fry & Hale, 2000). This research is an attempt to add to the knowledge by filling this research gap.

The third issue presented by Fry & Hale (2000) explored how developmental increases in processing speed, working memory and intelligence affect each other. For school-age children, the evidence suggests age-related improvements on intelligence tests were due to developmental improvements in working memory. However, for pre-school students, much of the age-related improvement in intelligence test scores appears to be due to increases in speed of processing.

Importantly, virtually all of the effect of the age-related increase in speed of processing appears to be mediated through the effect of speed on working memory, as suggested by Kail and Salthouse (1994). Moreover, virtually all the effect of improvements in working memory on intelligence is itself attributable to the effect of improvements in speed on working memory, providing further evidence of a cognitive developmental cascade. (Fry & Hale, 2000, p. 30)

The Impact of Processing Speed, Working Memory and Intelligence on Academic Achievement

While it may seem obvious that intelligence and academic achievement are linked, the relationship between processing speed and academic achievement is not as clear. The same is true for working memory and academic achievement. This study investigates the research presented regarding reading and mathematics achievement and the influence speed of processing, working memory and intelligence have on these two content/skill areas.

Reading is widely held as the most fundamental skill students need to master in order to be academically successful (Breznitz, 2005; Farquhar, 1968; Hall 2006; Irwin 1967). In order to be a successful reader, one must be able to read fluently and accurately, remember what has been read, and use the information to draw inferences, develop conclusions, and create meaning. Students with diminished speed of processing and poor working memory often need additional support to become competent readers (Hall, 2006). Because reading is such a fundamental skill, determining the causal basis for reading difficulty is of critical importance to educators.

Many recent studies have linked a deficit in speed of processing to poor reading performance (Fletcher, et al., 1994; Olson, Datta, Gayan, & DeFries, 1999; Torgesen, Wagner, & Rashotte, 1994; Vellutino, Scanlon, & Spearing, 1995; Wolf & Bowers, 1999). Reading appears to be a cognitive ability that depends heavily on efficient processing speed. Skilled reading requires "the rapid recognition of letters and words and the access to and simultaneous integration of semantic, syntactic, and text-level information" (Catts, Gillispie, Leonard, Kail, & Miller, 2002, p. 520). Because of the time-dependent nature of reading, it makes sense that diminished speed of processing would have a significant impact on reading achievement (Catts, et al., 2002).

In a study by Catts et al. (2002) good readers, normal-IQ poor readers and low-IQ poor readers were considered. ‘Good readers’ were those who could read grade level text with minimal errors and effective comprehension. They compared students’ response time across linguistic and nonlinguistic tasks. The results showed poor readers performed significantly slower than good readers on response time tasks across linguistic and nonlinguistic domains. Significant differences were found between good readers and normal-IQ poor readers in motor, lexical, grammatical, and phonological response time domains. The same was true between good readers and low-IQ poor readers in all the response time domains. Both poor reader groups also performed significantly slower than good readers on the rapid object-naming task. “Taken together, these results demonstrate that poor readers may have a domain-general deficit in speed of processing…poor readers were significantly slower than good readers on the response time tasks” (Catts, et al.). The results suggest the students’ performance on the rapid naming tasks, as it relates to reading achievement, may reflect a generalized deficit in speed of processing. Furthermore, the results seem to support the hypothesis that “many children with reading disabilities have a deficit in speed of processing” (Catts, et al., p. 519).

Similar findings were stated by Wolf, Bowers and Biddle (2000) but with even more conviction: the vast majority of children with reading difficulties had “pronounced difficulties when asked to name rapidly the most familiar visual symbols and stimuli in the language” (Wolf, et al., 2000, p. 387) such as letters and numbers. Furthermore, they found naming speed is an accurate predictor of reading skills across several languages other than English, including German, Finnish, Dutch, and Spanish. This is important because it demonstrated that the irregularity of English orthography (rules of spelling and pronunciation) is not an explanatory factor in the RAN/reading achievement findings. They went on to explain that naming speed, especially the serial naming found in RAN tasks, provided an early approximation of the reading process. This is particularly important as we begin to think about how educators may apply this understanding of RAN results. When young readers struggle to identify individual letters, then single letters within a word will not be "activated in sufficiently close temporal proximity to allow the child to become sensitive to letter patterns that frequently co-occur in print" (Wolf, et al., 2000).

As mentioned earlier in this chapter, there is evidence that speed of processing and intelligence overlap considerably and that speed of processing is a central construct of intelligence (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002). However, Catts et al. (2002) posed the question: does speed of processing account for *unique* variance in reading achievement, beyond what is determined by intelligence alone? Their results indicate "the association between speed of processing and reading achievement goes beyond IQ, at least as IQ is commonly measured in relationship to reading achievement" (Catts et al., 2002). Their results add to the growing research that speed of processing is a unique contributing factor to reading achievement.

Other researchers question this finding, and extend the debate to include working memory. Essentially, scholars in the field question whether speed of processing *alone* leads to reading difficulty. Breznitz (2005) conducted a large analysis of literature and concluded that there is a significant difference in the speed of processing between good readers and poor readers. However, she goes on to explain that while poor readers struggle with slowness in processing information in general, they also struggle with slowness of processing information in their working memory. More specifically, proficient readers can complete RAN tasks virtually automatically – they can see, identify and name letters, numbers and colors without taxing their cognitive resources. However, poor readers struggle to do this with automaticity, and thus depend on cognitive resources, such as memory, to complete the tasks and other resources to relay the message aloud. She concluded diminished working memory capacity was a larger contributing factor to reading difficulty than slow speed of processing (Breznitz).

Just as there is evidence that working memory can have an impact on reading performance, many recent studies also support the notion that working memory is related to and important for performance on mathematical tasks. As defined earlier in the chapter, working memory is akin to the desktop of the mind; it is the "place" where one holds on to information that will be used to accomplish a task. Competence in mathematics requires a wide variety of complex skills that requires remembering pieces of information and processing of new information to arrive at a solution. This "holding on to information" while simultaneously using it to solve a problem is precisely what the working memory does. Therefore, it stands to reason that working memory and mathematics achievement should be closely related. Raghubar, Barnes and Hecht (2010) agree: "The very nature of many mathematical tasks would seem to require or at least be supported by working memory" (p. 210).

Through their meta-analysis, Raghubar, et al. (2010) found verbal working memory measures that involved numbers could be used to identify students with mathematics difficulties, but working memory measures that were non-numerical (using words rather than numbers) did not distinguish children with mathematics difficulties (Raghubar, et al., p. 113). In contrast, they also noted verbal working memory tasks, such as listening span, could predict student performance on computation, concepts and applications, and word problem solving, but did not predict performance on math-fact fluency assessments or standardized calculation measures (Raghubar, et al., p. 117). These findings suggest working memory does play a role in mathematics achievement but "there also appears to be some specificity in this relation; for example, the role of verbal working memory may be greater for some aspects of mathematics than it is for others" (Raghubar, et al.). Furthermore, their research highlights the fact that the relationship between working memory and mathematics is complex and depends on several factors including age, skill level, format of presentation of mathematics problems, type of mathematics skill being presented, and whether that skill has already been mastered or is still under construction (Raghubar, et al.). As evidenced by this list, there is still a need for a comprehensive model of mathematical processing which accounts for the demands of working memory, particularly in relation to skill acquisition (Raghubar, et al.).

Research by Geary, Brown and Samaranayake (1991) have similar findings: "poor working memory resources contribute to poor mathematics achievement (p. 795). They go on to explain that having poor working memory resources may have "contributed to the apparent failure to develop adequate long-term memory representations of basic facts" (Geary, et al., 1991, p. 795). In other words, students with poor working memory may struggle to commit basic mathematics facts, such as addition and multiplication facts, to long-term memory. When students struggle with basic mathematics facts, the likelihood of making errors during multi-step mathematics problems increases, such as when solving long division problems or reducing fractions. Ultimately, Geary, et al. found there were two primary factors contributing to early learning problems in mathematics: difficulty retrieving facts from long-term memory and poor working memory resources. As mentioned above, poor working memory makes it difficult for students to commit facts to long-term memory, so both of these factors exacerbate the other (Geary, et al., 1991).

In a study of 170 first grade students, Passolunghi, Vercelloni and Schadee (2007) found tests of working memory and counting were the most predictive of early mathematics learning. However, phonological ability did not appear to be involved in mathematics learning. Additionally, intelligence level did not demonstrate any significant influence for mathematics capacity (Passolunghi, et al., 2007). This particular study made an effort to delineate specifically between the effects of short-term memory and working memory, in order to verify possible roles of each capacity on mathematics ability. As was found in previous studies, Passolunghi, et al. also found working memory is a "distinct and significant predictor of mathematics learning" (p. 180) for primary age students. Additionally, they found that the short-term memory tasks did not show a causal relationship with mathematic achievement.

Interestingly, a study conducted by Hecht, et al. (2001) found phonological processing *does* influence mathematics achievement. These results stand in opposition to the findings of Passolunghi, et al. (2007). The authors explain phonological awareness tasks are good predictors of mathematics skills because both domains require skills in phonological memory and executive function. More specifically, children must "encode and maintain accurate phonological representations of terms and operators in phonological memory, while simultaneously operating on that information by selecting, implementing, and monitoring strategies used to solve the problem" (Hecht, et al., p. 197). For example, counting uses these skills in that the student must monitor the number just said and the number following it.

As was mentioned in the previous research studies, the results of the Hecht et al. (2001) study concur that phonological memory, a form of working memory, may also influence a student's ability to retrieve basic mathematic facts from long-term memory. When students are able to encode and use phonological information efficiently, they can devote all of their attention to solving mathematical problems (Hecht et al., 2001). Ultimately, Hecht et al. found "phonological processing significantly contributed to growth in mathematic computation skills, but a substantial proportion of the variance remained unexplained" (p. 218). In other words, the study does not provide an explanation for how each kind of phonological processing ability hinders or helps learning, remembering, and using mathematic concepts and skills. Because phonological processing is considered critical to the development of reading skills, the authors suggest, "to some extent a common cognitive pathway exists for the development of both reading and mathematics computation in young children" (p. 219).

Despite the contradictions throughout the research, one common theme seems to come through: working memory does contribute to mathematics achievement. While some argue working memory itself is the causal element, (Passolunghi, et al., 2007; Powell, et al., 2007) Hecht et al. (2001) argue, "working memory demands of phonological awareness tasks are primarily responsible for the relations between phonological awareness and math skills" (p. 219). Nonetheless, working memory is widely held as a critical element in mathematic achievement.

In a study by Gersten, Jordan, and Flojo (2005), evidence was presented that indicated that with adequate instruction, students with mathematic deficiencies can make progress in learning algorithms, procedures and basic word problems. However, their ability to remember basic mathematic facts (3+4=7) with speed and accuracy remains unchanged and poor. Gersten, et al. (2005) believe failure to "instantly retrieve a basic combination often makes discussions of the mathematical concepts involved in algebraic equations more challenging" (p. 294). Just as fellow researchers hypothesized, Gersten, et al. believe mathematic fluency, or ability to answer simple mathematic problems quickly and efficiently, is an accurate predictor of future mathematic success. Students who can work through basic mathematic fact problems quickly and accurately are more likely to demonstrate proficient mathematic achievement in later grades, while students who struggle with these basic skills will continue to struggle learning new concepts. While Gersten, et al. do not use the phrases “working memory” or “speed of processing,” the deficiencies they describe with delayed retrieval of mathematic facts seems to mirror what fellow researchers also found – diminished speed of processing and impaired working memory contribute to mathematic difficulties in children.

The body of research about the relationship between intelligence, speed of processing and working memory is vast, but contradictory at times. Researchers have tried to determine which factor is the *most* important in cognition, which factors help to predict academic achievement and how those factors influence each other, but there is certainly no consensus at this time.

While there has been ample research conducted about the nature of reading difficulties, there is still debate regarding the mechanism and specific causes of reading impairments. The research regarding mathematic difficulties is less robust, and arguments about which cognitive function plays the biggest role (working memory, phonological processing, fluid intelligence) are still playing out in the discourse. Nonetheless, the evidence suggests diminished speed of processing and poor working memory lead to a lack of academic fluency in both reading and math. This lack of fluency makes it difficult for students to read accurately and impairs comprehension. In mathematics, it limits the ability to recall basic mathematic facts with automaticity, thus hampering accuracy and production overall.

Implications for Teachers and Students

By understanding the cognitive profile of students with diminished speed of processing, teachers can gain an understanding of possible strengths and weaknesses of these students. In other words, if a teacher has a better understanding of a student's needs, that teacher can cater instruction appropriately. If a teacher assumes a student with low speed of processing is not intelligent, that teacher is likely to set low expectations for that student, which can limit the student's learning (Hall, 2006). Additionally, if a teacher assumes a student with a speed of processing deficiency is simply lazy or not trying, there can be enormous consequences for that student including low self-esteem, low motivation, and academic failure (Purkey, 1970).

The implications for students cannot be overstated: teachers who understand students' needs have an enormous impact on student achievement (Daniel & King, 1995; Farquhar, 1968; Friedland, 1992; O'Connor, 2008). When students achieve academic success, they are more likely to have financial and emotional health in their future (Daniel & King). If the goal of public educators is to help prepare students for their lives after graduation, any information which will inform better instruction is worthwhile and important.

CHAPTER III: METHODS

Introduction

The research method for this study is a correlational design, exploring the relationship between student's speed of processing, aptitude, working memory and academic achievement in reading and mathematics. Below, I describe my sample and assessment instruments used to measure each of these constructs. I also explain the steps I took to collect student data, and the statistical tests I conducted to analyze these data.

Participants and Site

For this ex post facto study, I used a convenience sample of students referred to me by homeroom teachers from second and third grade classrooms in an elementary school in southeast Fort Collins, Colorado. Teachers referred these students because they wanted additional diagnostic information about how the students process phonological information. My sample includes 72 students who fall into one of four cohorts: poor speed of processing, poor memory, double deficit (students who have below average speed of processing AND below average working memory) and no deficit. The sample represents 36 students who scored below average on the rapid naming portion of the Comprehensive Test of Phonological Processing (CToPP). Of these 36, 15 students also demonstrated below average memory skills. The sample also contains an additional 24 students who scored average or above average on the rapid naming and working memory portions of the test. Students in the sample were assessed in either second or third grade, but the scoring of each assessment is based on the specific age (year and month) of the student at the time of assessment. See Table 1.

Table 1
Sample Scale Scores Comparison

Cohort	**Number of Students**
Low Speed of Processing	21
Low Working Memory	12
Double Deficit	15
No Deficit	24

When a student has difficulty learning or producing work, the teachers in the school used for this study employ several techniques to support them. Differentiated instruction, or specialized instruction for each individual student, is utilized regularly and students are taught in small group environments, particularly in reading and mathematics, most of the time. This allows teachers to move between and among groups, providing specific attention and direction as needed. The school where this study was conducted is fortunate to have consistent parent volunteers who help facilitate this structure, providing an extra set of eyes, ears and hands to help answer questions and provide support, so teachers can do the important work of providing explicit instruction. On certain occasions, however, teachers find that they have a student who is struggling and the cause is not clear. The reasons are varied and multiple, but often when a teacher just cannot seem to determine how to best help children with their learning, I am asked to provide additional assessment. This is the referral process that led to my sample of 72 students. In other words, each student in the cohort was not making adequate progress, not demonstrating proficiency, or not meeting the general expectations the teacher held.

Particularly because of this referral process, my sample is not representational of the theoretical population of all second and third graders, and thus, I would rate this as low population external validity. However, I believe I have medium to high ecological external validity because the conditions in which the students completed the assessments were very natural as they took the tests either in a classroom that they were in daily, or individually with me. Rapport with testers was presumably very high because their teachers, or an interventionist that they worked with regularly, proctored the students during the MAP and CogAT assessments. Furthermore, I did have a prior relationship with each student, so students were comfortable during the CToPP test as well. Finally, the procedures, timing, and length of the assessments were not unique in that students have been exposed to standardized testing throughout their tenure in public school.

The internal validity of my study is medium to high in that I was the only proctor who administered the CToPP assessment to the entire sample. I followed the script carefully and did not deviate from the directions provided within the CToPP instruction manual. Furthermore, each student participated in the MAP achievement tests and CogAT assessment in a standardized environment as well. Their homeroom teacher monitored students carefully, ensuring students understood the directions, had the test materials they needed, and attended to the assessment. The teachers were well trained to follow the directions required for both tests. All students in the sample received standardized administration of all the assessments used for this study.

Table 2
Description of Measures and Variables: Each of the assessments used, how it was conducted, and what it measures.

MEASURE	IV or DV	Description of the measure	Construct measured
CToPP – Rapid Naming	IV	• Comprehensive Test of Phonological Processing – Rapid Automatized Naming • Timed, oral response	Speed of Processing
CToPP – Memory	IV	• Comprehensive test of Phonological Processing – digit span and nonsense word repetition • Timed, oral response	Working Memory
MAP math	IV	• Measures of Academic Success – math computation • Not timed, computer-based	Academic achievement in mathematics
MAP reading	IV	• Measures of Academic Success – reading skills • Not timed, computer-based	Academic achievement in reading
CogAT Verbal	DV	• Cognitive Abilities Test – verbal reasoning • Not timed, paper/pencil response	Cognitive capacity in verbal skills
CogAT Quantitative	DV	• Cognitive Abilities Test – quantitative reasoning • Not timed, paper/pencil response	Cognitive capacity in math skills

In addition to the CToPP, I also used the results of students' Cognitive Abilities Test (CogAT) for verbal and quantitative reasoning, as well as the Measures of Academic Progress (MAP) assessment for reading and math. As indicated in Table 2, The CToPP assessment provides a measure of students' speed of processing, the CogAT is a measure of cognitive capacity or fluid intelligence, and the MAP tests represent students' academic achievement in reading and in math. While I am predominantly interested in the ways speed of processing are related to intelligence and academic achievement, it became clear while researching this topic, I must also address students' working memory capacity, as working memory and speed of processing are intricately linked. Therefore, I also used the working memory score from the CToPP assessment. These assessment results helped me to answer the following research questions:

RQ1.) How well can I predict students' aptitude scores (CogAT) from a combination of three variables: MAP, CToPP rapid naming and CToPP working memory?

1.1) How well can I predict students' verbal aptitude scores (CogAT Verbal) from a combination of MAP reading, CToPP rapid naming and CToPP working memory scores?

1.2) How well can I predict students' quantitative aptitude scores (CogAT Quantitative) from a combination of MAP math, CToPP rapid naming and CToPP working memory scores?

RQ2.) What is the strength of the correlation between speed of processing and aptitude in verbal and quantitative reasoning?

RQ3.) What is the strength of the correlation between speed of processing and academic achievement in reading and mathematics?

RQ4.) Is there a difference in aptitude and academic achievement between the four cohorts?

- Low speed of processing only?
- Low working memory only?
- Double deficit (low processing speed and low working memory)?
- No deficit?

RQ5.) What is the strength of the correlation between speed of processing, working memory, aptitude, and academic achievement for each individual cohort?

- Low speed of processing only?
- Low working memory only?
- Double deficit (low processing speed and low working memory)?
- No deficit?

Measures

Comprehensive Test of Phonological Processing (CToPP)

Elementary educators use assessments to illuminate potential problems, identify student strengths and skill deficits, or sometimes simply validate a teacher's intuition of skill level for a student. One of the most involved but informative of these assessments is the Comprehensive Test of Phonological Processing (CToPP). The CToPP provides subtests for three overarching domains: working memory, phonemic awareness and rapid naming (Wagner, Torgesen, & Rashotte, 1999). It is a nationally normed assessment and provides a composite score and an age-based percentile.

Wagner, et al. (1999) designed the CToPP assessment to meet six specific requirements outlined by professionals working in education, psychology, and speech and language pathology. The CToPP is a test which: (1) measures reading related phonological skills, (2) provides the examiner with a comparative index of phonological processing strengths and weaknesses, (3) provides sufficiently reliable results so that the examiner can have confidence when used with individuals, (4) provides sufficiently valid results so the examiner will know what abilities are being measured, (5) is short enough that the fatigue of both examiner and examinee is held at a minimum, and (6) has norms that are based on a large normative sample that includes representative of a broad spectrum of Americans (Wagner, et al., 1999).

The CToPP test assesses phonological awareness, phonological memory and rapid naming. A deficit in one or more of these phonological processing abilities is believed to be the most common cause of learning disabilities in general, and of reading disabilities in particular (Wagner, et al., 1999, p. 7). However, as mentioned in Chapter two, phonological processing abilities also support effective mathematical calculation (Geary, et al., 1991; Gersten, et al., 2005; Hecht, et al., 2001). The CToPP was developed to:

> help identify individuals who may need additional instructional support to improve phonological skills, to determine strengths and weaknesses among developed phonological processes, to document individual progress in phonological processing, and to serve as a measurement device in research studies investigating phonological processing. (Wagner, et al., 1999, p. 13)

The CToPP was normed on a sample of 1,656 persons in 30 states (chosen from each of the four major geographic regions – Northeast, Midwest, South and West) and includes the following demographic characteristics: geographic area, gender, race, residence (urban/rural), ethnicity, family income and education of parents. The normative sample is representative of the nation as a whole based on U.S. Census data at the time of norming. Norms for the CToPP composite scores are based on a distribution having a mean of 100 and a standard deviation of 15. These distributions were selected because they are already well known to examiners who use common intelligence tests for children (Wagner, et al., 1999, p. 62).

The CToPP assessment meets the requirements to be considered reliable. The authors examined three sources of error variance – content sampling, time sampling, and interscorer differences. Regarding content sampling, 100% of the alphas for the CToPP subtests reach .70, 76% attain .80, and 19% attain .90. However, the alphas for composite scores are larger, and all coefficients that relate to the composite scores exceeded .80, indicating they meet the minimal reliability expectation (Aiken, 1994). For this study, the more reliable composite scores will be analyzed. Furthermore, additional evidence is presented to show that the CToPP is equally reliable for all the subgroups investigated and "support the idea that the test contains little or no bias relative to those groups" (Wagner, et al., 1999, p. 70).

Using a test-retest method, the CToPP demonstrates stability over time. Using a sample of 91, students were tested twice within a two-week period. The reported values are of sufficient magnitude to allow confidence in the test scores' stability over time (Wagner, et al., 1999, p. 73). Correlation coefficients ranged between .68 and .97 for the five to seven-year range, .72 to .93 for eight to 17, and .67 to .90 for 18 to 24 years (Wagner, et al.).

Convincing evidence is also presented to demonstrate the test's scorer reliability. To determine inter-rater reliability, two staff members at PRO-ED (the Publishing company for the CToPP assessment) independently scored 30 protocols from five- and six-year-olds and 30 protocols from seven- to 24-year-olds. Results were reported to be .98. This indicates high inter-rater reliability.

Overall, the CToPP evidences a high degree of reliability, and is consistently high across all three types of reliability—content, time, and scorer: "the magnitude of these coefficients strongly suggests that the CToPP possesses little test error and that users can have confidence in its results" (Wagner, et al., 1999, p. 73).

Wagner, et al. (1999) offer three demonstrations of content validity for the CToPP: detailed rational of the selection of items and subtest formats, Item Response Theory analyses used during the developmental stages of test construction, and results of differential item functioning analysis, which shows the absence of bias in the test's items (Wagner, et al., p. 80).

Wagner, et al. (1999) chose each CToPP subtest based on an "experimental task that was used to study phonological processing in the published literature and was evaluated extensively in a decade of research" (p. 80). In order to provide qualitative evidence for the CToPP's content validity, experts in the field of phonological processing were asked to review and critique each subtest, and while the reviews were reported to be positive, the minor suggestions that did come forward were incorporated into a revised version of the CToPP. Before obtaining national norms, Wagner, et al. determined "adequate floors and ceilings" on each of the subtests for the range of potential examinees (p. 80). This was done by administering the CToPP to a sample of 142 students in a developmental research school in Florida, in which admission to the school is based on "a selection procedure that ensures the student body is comparable to the demographic makeup of students in the state of Florida" (Wagner, et al., p. 80). More specifically, the sample contained 25 students from grades kindergarten, second, fifth and seventh as well as 40 high school students. No additional subtest changes were made upon conclusion and the national standardization sample was obtained.

To provide quantitative evidence of content validity, Wagner, et al. (1999) used Item Response Theory Modeling. Using item discrimination and difficulty statistics, the corresponding parameters in the IRT models, and an examination of item and test information, unsatisfactory items were removed from the test. All test items that met the criteria for content validity were then ranked from easy to difficult and are included in the final version of the test (Wagner, et al.). Item analysis using the entire normative sample was done to demonstrate test items were satisfactory for all subtests, other than those that are timed. The timed subtests score differences are attributed to how quickly a student responds rather than difficulty of the item itself. The discrimination coefficients (corrected for part-whole effect) for the subtests range from .41 to .66 for the age intervals included in this study (Wagner, et al.). Discrimination indexes of .35 or higher are acceptable, so these results indicate appropriate evidence of content validity. The difficulty coefficients for subtests range from .21 to .75 for the age intervals in this study (Wagner, et al.). Items distributed between 15% and 85% are considered acceptable, so again, these results indicate appropriate evidence of content validity.

Although the discrimination and item difficulty analysis described above do provide evidence that the subtests of the CToPP "capture the variance involved in phonological processing," (p. 85). Wagner, et al. (1999) also chose to use "the logistic regression procedure for detecting differential item functioning (DIF)" to detect item bias (p. 86). The rationale for this decision was clearly explained by the authors:

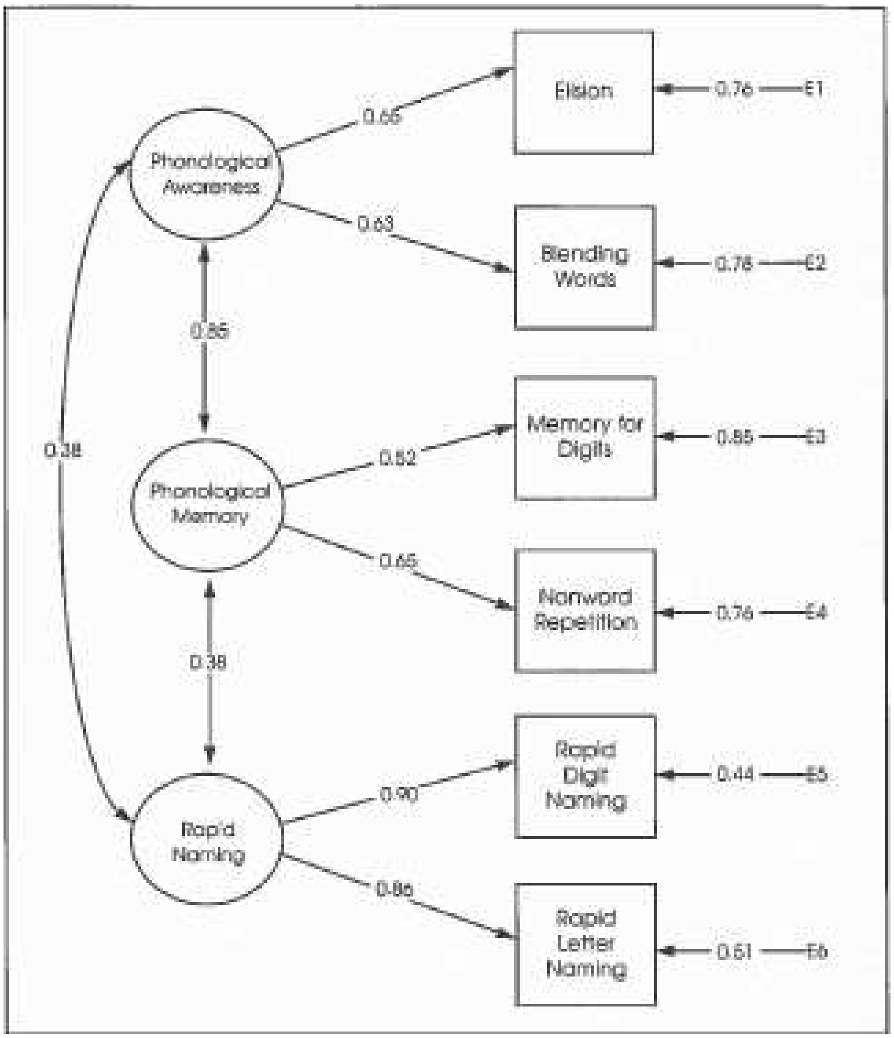
> The logistic regression procedure for detecting DIF is of particular importance because it provides a method for making comparisons between groups when the probabilities of obtaining a correct response for the groups is different at varying ability levels. The strategy used in this technique is to compare the full model (i.e., ability, group membership, and the interaction between ability and group membership) with the restricted model (i.e., ability alone) to determine whether the full model provides a significantly better solution. If the full model does not provide a significantly better solution than the restricted model, then differences between groups on the item are best explained by ability alone. (Wagner, et al., 1999, p. 86)

In other words, if the full model is not significantly better at predicting an item's performance than the restricted model, that item is measuring a difference in ability and does not indicate influence by belonging to the group; therefore, the item is not considered biased. For this procedure, Wagner, et al. (1999) created four dichotomous groups: male/female, European American/Non-European American, African American/Non-African American, and Hispanic American/Non-Hispanic American. Ultimately, 25 items were removed from the final version of the CToPP because "the item content was suspect" (Wagner, et al.).

Wagner, et al. (1999) also employed the Delta Scores approach to study bias within the CToPP in which any items with obvious difficulty differences are eliminated or changed to remove bias from a test. The reported correlation coefficients are between .86 and .99 for four dichotomous groups: male/female, European American/Non-European American, African American/all other races, and Hispanic Americans/all other ethnic groups. These coefficients indicate little bias for the groups analyzed.

In order to determine the construct-identification validity of the CToPP, confirmatory factor analysis was used to confirm that the factor structure of the CToPP matches the model upon which it is based. In other words, the three subtests of phonological awareness, phonological memory and rapid naming actually measure overall phonological processing. Wagner, et al. (1999) chose to use confirmatory factor analysis because they felt it could "provide a more rigorous test of construct validity than is provided by exploratory factor analysis" (p. 98). Specifically, Wagner, et al. state in confirmatory factor analysis, each subtest is permitted to load only on the factor that it represents, rather than on all factors, as in exploratory factor analysis. Furthermore, they explain with confirmatory factor analysis one has a test of the extent to which the model agrees with the data, and that is not available in exploratory factor analysis (Wagner, et al.). The model yielded a CFI of .99, and a chi square of 27.6, with six degrees of freedom. These results support the construct validity of the CToPP. Figure 2, below, illustrates the loadings of each subtest on each factor. Each arrow between constructs shows the factor loading which means how much or how well the factor explains the variable. Each variable had a loading over .4, which indicates construct validity for the CToPP.

Figure 2. Confirmatory factor analysis of the CToPP



The CToPP assessment is administered to students in a one-on-one setting. There is a specific script the examiner must follow, dictating exactly what to say for each section of the assessment. Students who take the CToPP are all subjected to the same experience, and the level of standardization for my sample is high. All students were tested by me, in my office, and away from their peers and other distractions following the script provided by the CToPP authors.

Measure of Academic Progress (MAP)

I used the Northwest Evaluation Association's (NWEA) Measures of Academic Progress (MAP) reading and mathematics test results from the fall of third grade as my measure of academic achievement for each of the students in the sample. The MAP test is also a nationally-normed assessment with results reported as a raw score and percentile. The MAP test is a computer-adaptive test in reading, language use, and math. Specifically, the program adjusts the difficulty of the questions based on students' responses. When a student answers a question incorrectly, the next question is slightly easier; when a student answers a question correctly, the next question is slightly harder. According to the NWEA website, this sort of adaptation will yield results that can help identify a student's strengths and weaknesses. Another purported benefit of the computer adaptive test is that it is shorter than a traditional paper-pencil assessment because it takes fewer questions to determine a student's specific achievement level (NWEA, 2015). More specifically, items on the MAP assessment are selected from a pool of Rasch-calibrated items, which means all items have been calibrated to the same scale. Therefore, "different tests that may be constructed in a domain are all children from the same parent, and scores from different tests constructed from that domain can be interpreted in the same manner" (NWEA, 2012 p. 3).

The MAP assessments were designed based on six guiding principles. The assessment should:

1. Be challenging for a student across all its test items, not be frustrating or boring.
2. Be economical in its use of student time.
3. Provide a reflection of a student's achievement that is as accurate and reliable as needed for the decisions to be made on its results.

4. Consist of content the student should have had an opportunity to learn.
5. Provide information about a student's change in achievement level from one test occasion to another as well as the student's current achievement level.
6. Provide results to educators and other stakeholders as quickly as possible while maintaining a high level of integrity in the report results (NWEA, 2012, p. 5).

The MAP tests are not timed so students have as much time as they need to respond to each question. As discussed in the previous chapter, this places less demand on working memory and has several obvious implications for students with impaired speed of processing. This was particularly appealing to me, as this study will explore how students with impaired processing speeds perform academically. A timed test may inadvertently lower apparent achievement; students may know or be able to come up with the correct answer if given enough time to think and process but may answer incorrectly if they feel rushed. Students are encouraged to take their time and work carefully on the MAP tests, so processing speed should not be a contributing factor to a student's achievement or score on this assessment.

The MAP Technical Report provided by the NWEA provides evidence of validity and reliability, including reliability coefficients derived from the norm sample for MAP. With rare exceptions, these measures indicate strong interrelationships among the test items for these assessments (NWEA 2011, Northwest Evaluation Association, 2012).

Because the MAP tests are adaptive, the authors examined reliability using different methods than one might traditionally find. Specifically, test-retest reliability is impossible because the same test cannot be administered to the same students due to the dynamic item selection used by the program. Parallel forms reliability is also practically impossible because the difficultly level of the question presented is based on the student's response to the prior question. NWEA states they have used a combination of test-retest reliability and a type of parallel forms reliability, both of which were spread across several months (rather than the traditional two or three weeks). The retest is not the exact test students took before, but is comparable in its content and structure. "Thus, both temporally-related and parallel forms of reliability are framed here as the consistency of covalent measures taken across time" (NWEA, 2011, p. 55). NWEA refers to this as stratified, randomly-parallel form reliability. Reported correlations for the reading MAP are between 0.73 and 0.83, which indicates medium to high reliability. For the mathematic MAP, reported correlations are between 0.74 and 0.90, again indicating medium to high reliability.

The NWEA offers several common forms of validity evidence, predominantly from the relationships of MAP test scores to state content-aligned accountability test scores (NWEA, 2011, p. 182). These relationships include:

- Test content
- The concurrent performance of students on MAP tests with their performance on state tests given for accountability purposes
- The predictive relationship between students' performance on MAP tests with their performance, two testing terms later, on state accountability tests
- The relationship between students' performance on MAP tests and their normative status relative to criteria defined by their state's achievement standards

Content validity was developed by "carefully mapping into a test blueprint the content standards being used by the educational entity commissioning the test" (NWEA, 2011, p. 182). Concurrent validity, expressed in the form of a Pearson correlation coefficient, was calculated between the scale scores of the MAP tests and the total scale scores from other established tests designed to assess the same domain area. Both tests were administered to students, roughly two weeks apart. Concurrent validity was indicated for the reading and mathematics MAP tests, with correlation values ranging from 0.72 to 0.83, indicating medium to strong concurrent validity.

Predictive validity was expressed as a Pearson correlation coefficient between the total domain area score for the MAP test and the total scale score of another established test in that same domain (i.e. reading or mathematics). In this case, students took the MAP test followed by the different assessment 12 to 36 weeks later. Reported correlation values were between 0.63 and 0.8 for reading and between 0.49 and 0.83 for math. The manual cautions that "correlations with non-NWEA tests that include more performance test items that require subjective scoring tend to have lower correlation than when non-NWEA tests consist of exclusively multiple-choice items" (NWEA, 2011, p. 187).

Finally, criterion-related validity was reported using the correlation between the MAP scores and student performance at the proficient level or above on a state assessment as the external criterion (NWEA, 2011). The Pearson Product-Moment correlations were between 0.46 and 0.66 for reading, and between 0.52 and 0.69 for math. These correlations for criterion-related validity are lower than the other validity evidence presented. However, NWEA states that because the relationship between a MAP score and the dichotomous proficient/not proficient designation is expressed as a point-measure correlation, "these correlation coefficients will always be smaller than a correlation coefficient calculated from both test performances expressed as scale scores" (NWEA, 2011, p. 190).

Cognitive Abilities Test (CogAT)

To determine cognitive capacity, I examined the results of the Cognitive Abilities Test (CogAT). The CogAT is not an achievement test, but rather a nationally normed aptitude test, so it is considered a reasonable equivalent to an intelligence test (Lohman, 2012). Like an IQ test, it only measures a person's aptitude or propensity for strength (or weakness) in verbal, non-verbal/spatial, and quantitative reasoning. Just because a student has an aptitude in a given area does not mean he or she will actually achieve well in that area (Lohman, 2012b) I will examine the results of the verbal and quantitative portion of the test only, as I do not have an achievement counter-point for the non-verbal section; the MAP reading and mathematics test provides this comparison for the verbal and quantitative portion of the CogAT.

According to its authors, the CogAT evaluates the abstract reasoning abilities that are needed for academic success. The test was originally published in 1954 and titled *The Lorge-Thorndike Intelligence Tests*. The word intelligence was removed from the title in 1968 due, in part, to the wide discrepancy and debate about the definition of intelligence, as referenced in Chapter two of this study. Rather, the authors decided that what the test actually measures is cognitive ability or the cognitive processes students utilize while taking the assessment, so the new name *Cognitive Abilities Test* was used instead (Lohman, 2012, p. 4).

The CogAT is administered as three separate batteries: verbal, quantitative and nonverbal. For the purposes of this study, I only examined the verbal and quantitative scores because I do not have a related academic achievement score for the non-verbal portion of the test. Each section evaluates inductive and deductive reasoning that specifically relate to that battery. The composite score is considered a measure of overall cognitive ability in that area (Lohman, 2012, p. 6).

Internal consistency reliability of the CogAT was evaluated using a part-test method in which items from each battery were divided into odd and even half-tests. Because of the design of the CogAT, it was reasonable to expect each half-test to be parallel. Reliability coefficients for all levels of the test ranged from 0.86 to 0.97. This indicates high internal consistency reliability.

The validity evidence for the CogAT is presented in three ways:

> (1) evidence based on the content of the test tasks, particularly on the cognitive processes examinees typically use to solve them, (2) evidence based on the internal structure of the test, particularly the patterns of relationships among scores on the different subtests, and (3) evidence based on the relationships between student performance on CogAT and on other tests, particularly measures of school achievement. (Lohman, 2012, p. 68)

Correlations between Standard Age Scores on Form 7 of the *Cognitive Abilities Test* (*CogAT*) VERBAL and Standard Scores on Form E of the *Iowa Assessments*, a nationally normed assessment used for state level accountability, indicates reliability coefficients between 0.56 and 0.81when looking at the third-grade level. This is considered a medium to strong correlation.

Confirmatory factor analysis was performed to determine if the questions loaded as expected to the factors they predicted (verbal, non-verbal or quantitative). This analysis also validated that the sub-tests are measuring the construct of overall cognitive ability. The model yielded a CFI of .99, and a chi square of 321, with 108 degrees of freedom. These results support the construct validity of the CogAT (Lohman, 2012, p. 73).

Procedure

Using the percentile data for each of the assessments (CToPP rapid naming and working memory, CogAT verbal, CogAT quantitative, MAP reading and MAP mathematics), I converted students' percentile scores into a scale score, following the standard set in the CToPP manual. See Table 3 below for cut point and scale score conversions.

Table 3

Percentile to Scale Score Conversions: All assessment results were reported as percentiles, but then I converted them to a scale score.

Percentile	**Label**	**Scale Score**
Less than 2^{nd} percentile	Well below average	1
2^{nd} – 8^{th} percentile	Below average	2
9^{th} – 24^{th} percentile	Low average	3
25^{th} – 74^{th} percentile	Average	4
75^{th} – 90^{th} percentile	High average	5
91^{st} – 97^{th} percentile	Above average	6
98^{th} and above	Well above average	7

As illustrated earlier in Table 2, each assessment serves to measure one of the constructs I am exploring: speed of processing, working memory, academic achievement and aptitude. I used the percentile score for each of these assessments and converted those into a scale score, as seen in Table 3. By converting the percentile scores into scale scores, I conducted several statistical tests to investigate my fundamental questions.

Data Analysis

In order to answer my prediction questions (RQ1), I analyzed my data set using multiple regression. The MAP reading, and CToPP rapid naming and phonological memory scale scores were used as the predictor variables for the dependent variable, CogAT Verbal scale score for RQ1.1 [How well can we predict students' verbal aptitude scores (CogAT Verbal) from a combination of MAP reading, CToPP rapid naming and CToPP working memory scores?]. The MAP math, and CToPP rapid naming and phonological memory scale scores were used as the predictor variables for the dependent variable, CogAT Quantitative scale score for RQ1.2 [How well can we predict students' quantitative aptitude scores (CogAT Quantitative) from a combination of MAP math, CToPP rapid naming and CToPP working memory scores?]. The resulting models indicate how much of the variance in predicting students' verbal and quantitative aptitude scores can be explained by the MAP and CToPP results. The analysis of variance results indicate if there is a significant relationship between cognitive capacity (as indicated by the CogAT verbal and quantitative test) and one or more of the predictors (speed of processing, working memory, academic achievement in reading or math.)

To answer the correlation questions (RQ2 & 3), I computed the Pearson and Spearman rho correlations and calculated the effect size to determine the strength of the relationships between my constructs for each cohort of students. Specifically, this illustrates if there is a relationship between speed of processing, working memory, cognitive capacity and academic achievement between each cohort.

To answer the difference question (RQ4), I compared the results of each cohort (single deficit, double deficit, no deficit) using an Analysis of Variance (ANOVA) to determine if there is a significant difference in cognitive capacity and academic achievement. The ANOVA indicates if there is a significant difference between cognitive capacity and academic achievement for each of the following cohorts: single deficit: low speed of processing, single deficit: low working memory, double deficit: low speed of processing *and* low memory, and no deficit.

To answer the final correlation question (RQ5), I computed Pearson and Spearman rho correlations and calculated the effect size to determine the strength of the relationships between my constructs for each individual cohort of students. Specifically, this illustrates if there is a relationship between speed of processing, working memory, cognitive capacity and academic achievement for each cohort. This is different than RQ3 in that I am looking for correlations in one specific cohort at a time rather than correlations between the cohorts.

CHAPTER IV: FINDINGS AND RESULTS

Introduction

This chapter presents the findings of data analysis for the following research questions:

RQ1.) How well can we predict students' aptitude scores (CogAT) from a combination of three variables: achievement scores (MAP), speed of processing (CToPP rapid naming), and working memory (CToPP memory)

1.1) How well can we predict students' verbal aptitude scores (CogAT Verbal) from a combination of MAP reading, CToPP rapid naming, and CToPP working memory scores?

1.2) How well can we predict students' quantitative aptitude scores (CogAT Quantitative) from a combination of MAP math, CToPP rapid naming, and CToPP working memory scores?

RQ2.) What is the strength of the correlation between speed of processing and cognitive capacity in verbal and quantitative reasoning?

RQ3.) What is the strength of the correlation between speed of processing and academic achievement in reading and math?

RQ4.) Is there a difference in cognitive capacity and academic achievement between the four cohorts (low speed of processing, low working memory, double deficit, and no deficit)?

RQ5.) What is the strength of the correlation between speed of processing, working memory, cognitive capacity, and academic achievement for each individual cohort (low speed of processing, low working memory, double deficit, and no deficit)?

The following descriptive statistics include an overall descriptive table (Table 4) with a minimum, maximum, mean, standard deviation, and skewness for all assessments. There is positive skewness of the CogAT Verbal variable of 1.175, and CogAT Quantitative variable of .931. All other variables are approximately normal.

Table 4
Descriptive Statistics of Aptitude, Achievement and Processing Assessment Scale Scores

	N Statistic	Min. Statistic	Max. Statistic	Mean Statistic	Std. Deviation Statistic	Skewness Statistic	Skewness Std. Error
Speed of Processing	72	1	6	3.22	1.224	-.014	.283
Working Memory	72	2	6	3.64	.827	-.152	.283
Quantitative Aptitude (CogAT Q)	72	1	7	4.25	.931	-.094	.283
Verbal Aptitude (CogAT V)	72	3	7	4.33	.769	1.061	.283
Reading Achievement	72	1	7	3.83	1.175	-.149	.283
Math Achievement	72	2	7	4.08	.946	.755	.283
Valid N (listwise)	72						

To answer research question one, [How well can we predict students' cognitive capacity (CogAT) from a combination of three variables: achievement scores (MAP), speed of processing (CToPP rapid naming), and working memory (CToPP memory)], I analyzed the data set using multiple regression. The MAP reading/math, and CToPP rapid naming and memory scale scores were used as the predictor variables for the dependent variable, CogAT Verbal/Quantitative.

Simultaneous multiple regression was conducted to investigate the best predictors of students' verbal and quantitative aptitude scores. The means, standard deviations, and intercorrelations can be found in Table 5a. The combination of variables to predict verbal aptitude from achievement scores, speed of processing, and working memory was not statistically significant. Ultimately, the adjusted R^2 value was .025. This indicates only 2.5% of the variance in verbal aptitude scores was explained by the model. Therefore, for this sample, these variables do not give predictive information about verbal cognitive capacity. The beta coefficients are presented in Table 5b.

Table 5a

Means, Standard Deviations, and Intercorrelations for Verbal Aptitude and Predictor Variables (N=72)

Variable	***M***	***SD***	**1**	**2**	**3**
Verbal Aptitude (CogAT Verbal)	4.33	.77	.10	.13	.25
Predictor Variables					
1. Speed of Processing (CToPP Rapid Naming)	3.22	1.22	--	.04	.31
2. Working Memory (CToPP Memory)	3.64	.83		--	.26
3. Reading Achievement (MAP Reading)	3.83	1.18			--

Table 5b

Simultaneous Multiple Regression Analysis Summary for Speed of Processing, Working Memory, and Reading Achievement Predicting Verbal Cognitive Capacity (N=72)

Variable	***B***	***SE B***	***Beta***	***t***	***P***
Speed of Processing (CToPP Rapid Naming)	.02	.08	.03	.23	.822
Working Memory (CToPP Phonological Memory)	.06	.07	.07	.55	.582
Reading Achievement (MAP Reading)	.15	.22	.22	1.75	.084
Constant	3.49	.48			

In contrast, the combination of variables to predict quantitative aptitude from the same variables, was statistically significant, $F(3,68) = 10.3$, $p < .001$. The means, standard deviations, and intercorrelations can be found in Table 6a and the beta coefficients are reported in Table 6b. The adjusted R^2 value was .279. This indicates 28% of the variance in quantitative aptitude scores was explained by the model. According to Cohen (1988), this is a medium effect size.

Table 6a

Means, Standard Deviations, and Intercorrelations for Quantitative Cognitive Capacity and Predictor Variables (N=72)

Variable	**M**	**SD**	**1**	**2**	**3**
Quantitative Aptitude (CogAT Quantitative)	4.25	.93	.26*	-.01	.55**
Predictor Variables					
1. Speed of Processing (CToPP Rapid Naming)	3.22	1.22	--	.04	.43**
2. Working Memory (CToPP Memory)	3.64	.83		--	.13
3. Mathematics Achievement (MAP Mathematics)	4.08	.95			--

**p*<.05; ***p*<.01

Table 6b

Simultaneous Multiple Regression Analysis Summary for Speed of Processing, Working Memory, and Mathematics Achievement Predicting Quantitative Cognitive Capacity (N=72)

Variable	***B***	***SE B***	***Beta***	***t***	***P***
Speed of Processing (CToPP Rapid Naming)	.02	.09	.02	.21	.838
Working Memory (CToPP Phonological Memory)	-.09	.11	-.08	-.80	.426
Mathematics Achievement (MAP Mathematics)	.54	.11	.55	4.9	<.001
Constant	2.31	.56			

Note. R^2 = .31; $F(3, 68) = 10.27$, p <.001

This analysis indicates the CToPP and MAP assessment results can be useful to predict quantitative aptitude for this sample, but the model does not do an adequate job predicting verbal aptitude.

To answer research question two, [What is the strength of the correlation between speed of processing and verbal/quantitative aptitude?] a correlation was computed comparing the CToPP rapid naming variable and the CogAT verbal and quantitative variables. There is positive skewness of the CogAT Verbal variable of 1.175, and CogAT Quantitative variable of .931 which violate the assumption of normality. Therefore, the Spearman rho statistic was calculated. There was no statistically significant correlation of speed of processing and verbal aptitude nor quantitative aptitude; verbal and speed of processing: $r(70) = .11$, $p = .32$ quantitative and speed of processing: $r(70) = .15$, $p = .21$. There is no evidence of a correlation between processing speed and cognitive capacity in either verbal or quantitative aptitude for this sample. As I will discuss in the next chapter, this is an exciting finding and is contrary to what most of the literature suggests.

To answer research question number three, [What is the strength of the correlation between speed of processing and academic achievement in reading and math?] a correlation was also computed. Because all variables meet the assumptions of normality, the Pearson correlation coefficient was calculated to examine the intercorrelations of the variables. Table 7 shows that three of the three pairs of variables were significantly correlated. There is a statistically significant correlation at the .01 level between processing speed and academic achievement in reading and math; reading achievement and speed of processing: r (70) = .31, p = .008, mathematics achievement and speed of processing: r (70) = .43, p < .001. This indicates as processing speed increases, academic achievement in reading and math also increases. According to Cohen's (1988) guidelines, this is a medium effect size for both variables.

Table 7
Intercorrelations, Means, and Standard Deviations for Three Assessment Variables (N=73)

Variable	**1**	**2**	**3**	***M***	***SD***
1. Speed of Processing	--	.31*	.43*	3.22	1.22
2. Reading Achievement		--	.46*	3.83	1.18
3. Mathematics Achievement			--	4.08	.95

*p<.01

For research question four, [Is there a difference in cognitive capacity and academic achievement between the four cohorts?], I ran a one-way ANOVA with each cohort group (low speed of processing, low working memory, double deficit, and no deficit) as the factor and academic achievement (reading and math) and aptitude (quantitative and verbal) as the dependent variables.

When comparing verbal aptitude and reading achievement, there was a significant difference found among the cohorts on reading achievement scores, F (3, 68) = 4.51, *p* = .006, as reported in Table 8b. Table 8a shows the mean score on the MAP reading test was 3.43 for students with low processing speed, and 4.5 for students with no deficit. Post hoc Tukey HSD tests, reported in Table 8c, indicate the low processing speed cohort and no processing deficit cohort differed significantly in their scores on the MAP reading (reading achievement) test with a large effect size (*p* = .006, *d* = 1.1). This indicates students with impaired processing speeds scored significantly lower on the reading achievement test as compared to their peers with no processing deficits. Note this was not the case with verbal aptitude (CogAT) scores. So, while the data suggests students with low processing speeds do not have a significantly different verbal *aptitude* than their typical peers, they do demonstrate significantly poorer academic *achievement* in reading.

Table 8a

Means and Standard Deviations Comparing Processing Deficit Groups

Cohort		Reading Achievement Score (MAP reading)		Verbal Aptitude Score (CogAT Verbal)	
	n	*M*	*SD*	*M*	*SD*
1. Low Speed of Processing	21	3.43	.98	4.43	.93
2. Low working memory	12	3.50	1.00	4.33	.49
3. Double deficit	15	3.60	1.35	4.27	.88
4. No deficit	24	4.50	1.06	4.29	.69

Table 8b

One-Way Analysis of Variance Summary Table Comparing Deficit Cohorts on Reading Achievement Scores and Verbal Aptitude Scores

Source	***df***	**SS**	***MS***	***F***	***P***
Verbal Aptitude Scores					
Between groups	3	.299	.100	.16	.921
Within groups	68	41.701	.613		
Total	71	42.000			
Reading Achievement Scores					
Between groups	3	16.257	5.419	4.51	.006
Within groups	68	81.743	1.202		
Total	71	98.000			

Table 8c
Post-Hoc Tukey Test HSD Comparing Mean Differences Between Cohorts

Variable		Mean Difference	Std. Error	Sig.
Aptitude Verbal Scale Score				
Low Speed of Processing	Low Working Memory	0.095	0.283	0.987
	Double Deficit	0.162	0.265	0.928
	No deficit	0.137	0.234	0.936
Low Working Memory	Low Speed of Processing	-0.095	0.283	0.987
	Double Deficit	0.067	0.303	0.996
	No deficit	0.042	0.277	0.999
Double Deficit	Low Speed of Processing	-0.162	0.265	0.928
	Low Working Memory	-0.067	0.303	0.996
	No deficit	-0.025	0.258	1.000
No deficit	Low Speed of Processing	-0.137	0.234	0.936
	Low Working Memory	-0.042	0.277	0.999
	Double Deficit	0.025	0.258	1.000
Achievement Reading Scale Score				
Low Speed of Processing	Low Working Memory	-0.071	0.397	0.998
	Double Deficit	-0.171	0.371	0.967
	No deficit	-1.071*	0.328	0.009
Low Working Memory	Low Speed of Processing	0.071	0.397	0.998
	Double Deficit	-0.100	0.425	0.995
	No deficit	-1.000	0.388	0.057
Double Deficit	Low Speed of Processing	0.171	0.371	0.967
	Low Working Memory	0.100	0.425	0.995
	No deficit	-0.900	0.361	0.070
No deficit	Low Speed of Processing	1.071*	0.328	0.009
	Low Working Memory	1.000	0.388	0.057
	Double Deficit	0.900	0.361	0.070

**The mean difference is significant at the 0.05 level.*

When comparing quantitative aptitude and mathematics achievement, there was no significant difference found among any of the cohorts on any of the assessments. This means the students with impaired processing (speed or memory) did not demonstrate any significantly different assessment scores than their typical (non-impaired) peers on their aptitude or achievement tests for mathematics.

To answer research question number five, [What is the strength of the correlation between speed of processing, working memory, cognitive capacity, and academic achievement for each individual cohort?] I used data for each individual cohort only as opposed to the whole-group data set. Specifically, I looked at only the low speed of processing cohort (Cohort one) and compared their processing speed, working memory, cognitive capacity, and academic achievement to see if the profile of those students looks different than the profile of the other cohorts.

The following descriptive statistics include an overall descriptive table (Table 10) with a minimum, maximum, mean, standard deviation, and skewness for all assessments for Cohort one (low speed of processing.) There is positive skewness of the Working Memory variable of 2.829 and CogAT Verbal variable of 1.484. There is negative skewness of the CogAT Quantitative variable of -1.109 and the Reading Achievement variable of -1.019. All other variables are approximately normal.

Table 10

Descriptive Statistics of Processing, Aptitude, and Academic Achievement Scale Scores for Cohort 1 (Low Processing Speed)

						Skewness	
	N Statistic	**Min. Statistic**	**Max. Statistic**	**Mean Statistic**	**Std. Deviation Statistic**	**Statistic**	**Std. Error**
Speed of Processing	21	1	3	2.05	.669	-.052	.501
Working Memory	21	4	6	4.19	.512	2.829	.501
Quantitative Aptitude (CogAT Q)	21	1	6	4.24	1.044	-1.109	.501
Verbal Aptitude (CogAT V)	21	3	7	4.43	.926	1.484	.501
Reading Achievement	21	1	5	3.43	.978	-1.019	.501
Math Achievement	21	2	5	3.71	.784	-.801	.501
Valid N (listwise)	21						

Because assumptions of normality were violated for this cohort, I ran a Spearman correlation to determine if there was a statistically significant association between speed of processing, working memory, cognitive capacity, and academic achievement for students within this cohort. The analysis showed there is a significant correlation between speed of processing and quantitative aptitude, quantitative aptitude and verbal aptitude, quantitative aptitude and mathematics achievement, and verbal aptitude and reading achievement. Table 11 shows these four of the fifteen pairs of variables were significantly correlated. The strongest positive correlation was between speed of processing and quantitative aptitude, $r(21) = .71$, $p = <.001$, which is a large effect size according to Cohen (1988). The second strongest positive correlation was between verbal aptitude and mathematics achievement, $r(21) = .62$, $p = .003$, a medium effect size (Cohen). Finally, both quantitative aptitude and mathematics achievement as well as quantitative aptitude and verbal aptitude had the third strongest positive correction, *r*(21) = .52, *p* = .016, a medium effect size (Cohen).

Table 11
Intercorrelations, Means, and Standard Deviations for Six Cognitive Variables: Cohort 1 (Low Speed of Processing) (N=21)

Variable	**1**	**2**	**3**	**4**	**5**	**6**	***M***	***SD***
1. Speed of Processing	--	.37	.71*	.31	.06	.42	2.05	.67
2. Working Memory		--	.30	.02	-.12	.16	4.19	.51
3. Quantitative aptitude			--	.52*	.02	.52*	4.24	1.04
4. Verbal Aptitude				--	.09	.62**	4.43	.92
5. Reading Achievement					--	.31	3.43	.98
6. Math Achievement						--	3.71	.78

*p<.05 **p<.01

I conducted the same analysis using assessment results for Cohort two– low working memory. The following descriptive statistics include an overall descriptive table (Table 12) with a minimum, maximum, mean, standard deviation, and skewness for all assessments for Cohort two (low working memory.) There is positive skewness of the Speed of Processing variable of 2.055 and Math Achievement of 2.009. There is negative skewness of the Working Memory variable of -2.055 and the Reading Achievement variable of -1.964. All other variables are approximately normal.

Table 12
Descriptive Statistics of Processing, Aptitude, and Academic Achievement Scale Scores for Cohort 2 (Low Working Memory)

						Skewness	
	N Statistic	**Min. Statistic**	**Max. Statistic**	**Mean Statistic**	**Std. Deviation Statistic**	**Statistic**	**Std. Error**
Speed of Processing	12	4	6	4.33	.778	2.055	.637
Working Memory	12	2	3	2.83	.389	-2.055	.637
Quantitative Aptitude (CogAT Q)	12	3	7	4.67	1.231	.416	.637
Verbal Aptitude (CogAT V)	12	4	5	4.33	.492	.812	.637
Reading Achievement	12	1	4	3.50	1.000	-1.964	.637
Math Achievement	12	3	7	4.17	1.030	2.009	.637
Valid N (listwise)	12						

With only 12 students in this cohort, I recognize there is little power in these correlations, but I do hope to compare results across cohorts. Because assumptions of normality were violated, I ran a Spearman correlation to determine if there was a statistically significant association between speed of processing, working memory, cognitive capacity, and academic achievement for students within this cohort. As reported in Table 13, six of the fifteen pairs have statistically significant correlations. These are speed of processing and quantitative aptitude, speed of processing and verbal aptitude, speed of processing and math achievement, quantitative aptitude and verbal aptitude, quantitative aptitude and mathematics achievement, and verbal aptitude and mathematics achievement. The strongest correlation was between mathematics achievement and quantitative aptitude $r(12) = .84$, $p = .001$, followed by speed of processing and mathematics achievement, $r(12) = .77$, $p = .003$. The third strongest correlations were between speed of processing and verbal aptitude as well as speed of processing and quantitative aptitude both demonstrating the same level of correlation, $r(12) = .63$, $p = .03$. Based on Cohen's (1988) guidelines, these are all medium to large effect sizes.

Table 13

Intercorrelations, Means, and Standard Deviations for Six Cognitive Variables: Cohort 2 (Low Working Memory) (N=12)

Variable	**1**	**2**	**3**	**4**	**5**	**6**	***M***	***SD***
1. Speed of Processing	--	.20	.63*	.63*	.26	.77**	4.33	.78
2. Working Memory	--	--	.07	-.16	.26	.39	2.83	.39
3. Quantitative aptitude	--	--	--	.61*	.35	.84**	4.67	1.23
4. Verbal Aptitude	--	--	--	--	.40	.61*	4.33	.49
5. Reading Achievement	--	--	--	--	--	.33	3.5	1.00
6. Math Achievement	--	--	--	--	--	--	4.17	1.03

*$p<.05$ **$p<.01$

For cohort three (double deficit) I ran the same correlation matrix. The following descriptive statistics include an overall descriptive table (Table 14) with a minimum, maximum, mean, standard deviation, and skewness for all assessments for Cohort three (double deficit.) There is positive skewness of the Math Achievement of 1.357. All other variables are approximately normal.

Table 14

Descriptive Statistics of Processing, Aptitude, and Academic Achievement Scale Scores for Cohort 3 (Double Deficit)

						Skewness	
	N Statistic	**Min. Statistic**	**Max. Statistic**	**Mean Statistic**	**Std. Deviation Statistic**	**Statistic**	**Std. Error**
Speed of Processing	15	1	3	2.40	.737	-.841	.580
Working Memory	15	2	3	2.67	.488	-.788	.580
Quantitative Aptitude (CogAT Q)	15	3	5	4.13	.516	.282	.580
Verbal Aptitude (CogAT V)	15	3	6	4.27	.884	.116	.580
Reading Achievement	15	1	6	3.60	1.352	-.544	.580
Math Achievement	15	3	7	4.00	1.134	1.357	.580
Valid N (listwise)	15						

Again, due to the violation of assumptions of normality, I ran a Spearman correlation to determine if there was a statistically significant association between speed of processing, working memory, cognitive capacity, and academic achievement for students within this cohort. As reported in Table 15, six of the fifteen pairs demonstrated statistically significant correlations. They were speed of processing and reading achievement, working memory and verbal aptitude, quantitative aptitude and mathematical achievement, verbal aptitude and reading achievement, verbal aptitude and mathematics achievement, and reading achievement and mathematical achievement. The strongest correlation was between reading and mathematics achievement, $r(15)$, = .72, p = .002. This is considered a large effect size by Cohen (1988).

Table 15
Intercorrelations, Means, and Standard Deviations for Six Cognitive Variables: Cohort 3 (Double Deficit) (N=15)

Variable	1	2	3	4	5	6	*M*	*SD*
1. Speed of Processing	--	.07	-.09	.35	.72**	.29	2.40	.74
2. Working Memory		--	.21	.57*	.46	.40	2.67	.49
3. Quantitative aptitude			--	.29	.38	.71**	4.13	.52
4. Verbal Aptitude				--	.71**	.56*	4.27	.88
5. Reading Achievement					--	.72**	3.60	1.35
6. Math Achievement						--	4.00	1.13

*$p<.05$ **$p<.01$

Finally, for cohort four, the group of students with no processing deficits, I ran a correlation once again. The following descriptive statistics include an overall descriptive table (Table 16) with a minimum, maximum, mean, standard deviation, and skewness for all assessments for Cohort four (no deficit.) There is positive skewness of the Speed of Processing variable of 2.54, Working Memory of 1.91, Verbal Aptitude of 1.27 and Reading Achievement of 1.18. All other variables are approximately normal.

Table 16
Descriptive Statistics of Processing, Aptitude, and Academic Achievement Scale Scores for Cohort 4 (No Deficit)

						Skewness	
	N Statistic	**Min. Statistic**	**Max. Statistic**	**Mean Statistic**	**Std. Deviation Statistic**	**Statistic**	**Std. Error**
Speed of Processing	24	4	6	4.21	.509	2.539	.472
Working Memory	24	4	5	4.17	.381	1.910	.472
Quantitative Aptitude (CogAT Q)	24	2	6	4.13	.850	-.253	.472
Verbal Aptitude (CogAT V)	24	3	6	4.29	.690	1.271	.472
Reading Achievement	24	3	7	4.50	1.063	1.184	.472
Math Achievement	24	3	6	4.42	.830	.537	.472
Valid N (listwise)	24						

Due to the violation of assumptions of normality, I ran a Spearman correlation to determine if there was a statistically significant association between speed of processing, working memory, cognitive capacity, and academic achievement for students within this cohort. As shown in table 17, the only statistically significant correlation for this group was between quantitative aptitude and mathematical achievement $r(24) = .51$, $p = .010$. This is considered a large effect size, according to Cohen (1988).

Table 17
Intercorrelations, Means, and Standard Deviations for Six Cognitive Variables: Cohort 4 (No deficit) (*N*=24)

Variable	**1**	**2**	**3**	**4**	**5**	**6**	***M***	***SD***
1. Speed of Processing	--	.09	.06	.24	-.06	.18	4.21	.51
2. Working Memory	--	--	.06	.28	.25	.17	4.17	.38
3. Quantitative aptitude	--	--	--	.27	.09	.51*	4.13	.85
4. Verbal Aptitude	--	--	--	--	.03	.30	4.29	.69
5. Reading Achievement	--	--	--	--	--	.39	4.50	1.06
6. Math Achievement	--	--	--	--	--	--	4.42	.83

*p <.05

When looking at the results for each individual cohort, it is worth noting quantitative aptitude and mathematics achievement was significantly correlated in each matrix. The correlations between processing speed and test results for aptitude and achievement were mixed depending on the nature of the deficiency or lack thereof.

CHAPTER V: DISCUSSION

Introduction

I believe while many of us move quickly from one thought to another, barely pausing to consider if our thinking even makes sense, slower processing students prefer to dig deeper. They want to be sure of their answer, and compare their current thinking to past experiences. They operate in a slower, more methodical way—which is not to say they are slow learners. The pejorative nature of the word "slow" is part of the challenge these students face, in my opinion. Slow does not always mean bad; it can mean careful, contemplative, and/or mindful. These traits can lead to profound ideas. Teachers have an obligation to provide quality pedagogy to students who processes slowly. In order to do that, we need to gain a deeper understanding of what these students need and what they are truly capable of accomplishing.

Answering the Research Questions

In order to make sense of my findings, I will present each research question, why it was selected, and the ramifications of the results.

RQ1.) How well can I predict students' aptitude scores (CogAT) from a combination of three variables: achievement scores (MAP), speed of processing (CToPP rapid naming), and working memory (CToPP memory)?

As established, I am using aptitude scores as a proxy for general intelligence. This question attempts to determine if educators can predict how intelligent a student is based on his or her academic achievement scores, processing speed, and working memory. This question is held in two parts, one for mathematical aptitude and achievement, and one for verbal/reading aptitude and achievement.

For this sample, the model does not predict verbal aptitude. It is important to discuss what this means. In lay terms, and for this small sample, the combination of processing speed, working memory and academic achievement in reading does not adequately predict verbal intelligence. In fact, the results indicate only 2.5% of the variance in verbal aptitude scores was explained by the model.

However, when examining the data to predict quantitative intelligence using the variables of processing speed, working memory, and mathematic achievement, there is a statistically significant relationship: $F(3,68) = 10.3$, $p < .001$. These results indicate 28% of the variance in quantitative aptitude scores is explained by the model. What does this mean? For this sample, the predictor variables seem to predict quantitative intelligence/aptitude, at least to a certain extent.

As a researcher, I find this information exciting and unexpected. If the model predicts mathematic aptitude in a moderately good way, why does the model do such a poor job predicating verbal aptitude? As a teacher, however, it is difficult to know what to do with this knowledge. This research question sets the stage for deeper inquiry about how each individual predictor variable impacts intelligence and achievement. Perhaps it highlights evidence the cognitive mechanisms for proficient reading are different than those for mathematical proficiency.

RQ2.) What is the strength of the correlation between speed of processing and aptitude in verbal and quantitative reasoning?

This is the question that prompted my research. In essence, are slow processing students as capable as their peers in terms of their quantitative and verbal aptitude? Put another way, does speed of processing dictate how intelligent a student is? The analysis from question two attempts to answer this for my sample.

There was no statistically significant correlation of processing speed and verbal aptitude. Likewise, there was no statistically significant correlation of speed of processing and quantitative aptitude. In research, many are often deflated by lack of statistical significance. For me, it is cause for celebration (even if only a little bit.) This is evidence for my sample of students, aptitude in reading and mathematics is not related to processing speed in a significant way. To take this a step further, one could say that a student's speed of processing does not appear to be indicative of his or her intellectual capacity. I think these results are important in what they do not imply: there is no evidence that impaired processing correlates to poor cognitive capacity for this sample. This could have a potentially enormous impact on teacher's understanding of students with impaired processing. It indicates that there is no reason, based on this research, to assume a slow processing student is also unintelligent. Therefore, teachers should not lower their standards, assign false labels, or make assumptions about what a student may know or understand just because he or she may process slowly.

These results are decidedly different than those found by Jensen (1993), who believed that processing speed is the "purest manifestation" of intelligence. However, my results do closely match those of the Conway et al. (2002) study, which concluded processing speed and intelligence are not correlated, provided the task complexity is accounted for. Because RAN is not a complex task that taxes working memory, I was measuring processing speed alone.

Before discussing what these findings mean to me as an educator, I explore the results of research question three, the second half of this equation.

RQ3.) What is the strength of the correlation between speed of processing and academic achievement in reading and mathematics?

For this sample, there is a statistically significant correlation at the .01 level between processing speed and academic achievement in reading and in mathematics; reading and speed of processing: r (70) = .31, p = .008, mathematics and speed of processing: r (70) = .43, p = .000. This indicates as processing speed increases, academic achievement in reading and math also increases. It is interesting to juxtapose this information against the findings for research question two. While there was not a significant correlation between processing speed and *aptitude* there does appear to be a correlation between processing speed and *academic achievement*. Put another way, it appears that, despite the fact that it is at least possible students who process slowly may be as intelligent as their peers, they may be unable to achieve at the same level.

The discrepancy between a student's aptitude or capability and his or her performance is extremely important. As a teacher, the goal of helping students reach their potential is more than a cliché; it is what I work for each day. If a student has the capacity to learn, but is not learning, I believe inadequate instructional opportunities are to blame. As I will discuss further, we have an obligation to teach our students so they can learn. This may mean we need to adjust our practices and/or beliefs to support students with impaired speed of processing. If processing speed is a set characteristic, like an internal metronome that simply follows a beat that is unique to each individual, then educators need to adjust their teaching to match that pace. Educators need to allow time and space for different processing speeds. This includes those who are able to zip through assignments quickly, and those who need to sit and think before launching into action. Neither is right or wrong; neither is inherently good or bad.

It may be a function of the MAP test itself which explains these results. If students are doing well on the CogAT (measuring aptitude) but not on the MAP reading and mathematics tests (measuring achievement) I am inclined to explore what makes those tests different. For one, the CogAT test is taken in a traditional way, with paper and pencil. For the CogAT quantitative and verbal, there is very limited reading required. Most questions are abstract and wholly different than the test questions students usually encounter; most questions are posed as analogies (dog is to cat as _______ is to _______) which students do not often experience on a traditional school assessment. The CogAT is a timed test, and students often run out of time, which would normally be an enormous detriment to students with slow speed of processing – there does not seem to be evidence of that phenomenon with this sample, however. The MAP tests, in contrast, are computer based assessments, so students respond via multiple choice answers at the computer. It is not a timed assessment, and students have as much time as they need to complete both the reading and mathematics MAP assessments. I would have assumed this would be a better test scenario for students with impaired processing speed. Perhaps most importantly, the questions for the reading and mathematics test are language heavy, meaning there is often lengthy reading required to complete the question, even for mathematics questions. I will elaborate on this more below as this fact becomes relevant again when analyzing RQ5.

After examining the first three research questions, I find there is no significant relationship between processing speed and intelligence, but there is a significant relationship between processing speed and achievement. The students with low processing speed are not experiencing academic achievement like their peers who have average or above average processing speeds. These results stand to reason and are commensurate with the research

(Fletcher et al., 1994; Olson, et al., 1999; Torgesen, et al., 1994; Vellutino, et al., 1995; Wolf & Bowers, 1999).

RQ4.) Is there a difference in aptitude and academic achievement between the four cohorts (low speed of processing, low working memory, double deficit, and no deficit)?

With such a small sample size, particularly when breaking down the data set into four cohorts, the results of question four are dubious. However, I decided to proceed with this analysis out of curiosity. As a group, do the students with low processing speed have different results than students with no deficit at all? What about students who are low processing speed and poor working memory skills? In the end, there was only one significant difference; there was a significant difference between the results on the MAP reading test (reading achievement) between cohort one and cohort four (low speed of processing students and students with no processing deficit.) Other than that, there was no other significant difference on any assessment for any of the cohorts; there were no significant correlations when comparing quantitative aptitude and mathematics achievement among any of the cohorts on any of the assessments. Based on the research, one would expect students with low processing speed and/or impaired memory to perform worse than their non-impaired peers. The analysis does not show evidence of that for this sample. While RQ3 demonstrated a significant correlation between processing speed and math achievement, there does not appear to be a significant difference in scores between the cohorts for mathematical aptitude or achievement.

The results of this analysis are interesting because, despite the fact these cohorts represent students with differing processing capabilities, the clear majority of the assessments measuring cognitive capacity and academic achievement show no significant differences between the four groups (no deficit, low processing speed, low memory, and double deficit.) This may mean processing speed is not a good way to judge how capable a student is or how well he or she can do academically. This echoes my thoughts about RQ3: if processing speed does not correlate to intelligence but does correlate to academic achievement, *and* there is not a significant difference between assessment results for each cohort (other than for reading achievement in slow processing students vs students without a deficit), perhaps processing speed is not a good predictive variable. In other words, the evidence is mounting that, for this sample, processing speed is not indicative of intelligence, and is only limitedly indicative of academic achievement in reading and not at all for mathematics achievement.

I found no significant difference between any of the cohorts for reading other than students with low processing speed scored significantly lower on the reading achievement tests when compared to peers with no processing deficit. I also found no significant difference between *any* of the cohorts for mathematics (aptitude or achievement). Finally, I find that there is no significant difference between low processing students and those without a processing deficit (with the single exception of reading achievement.) I conclude that this evidence suggests that processing speed is not a good predictive variable.

The fact that all the students in this study were referred to me by their homeroom teachers is a very important consideration. Each of these students were identified by a teacher as presenting some sort of academic red flag. Therefore, whatever these students have in common may not be represented by these assessments alone. It is entirely possible another defining characteristic is hindering these students and creating a concern for the homeroom teachers.

RQ5.) What is the strength of the correlation between speed of processing, working memory, cognitive capacity, and academic achievement for each individual cohort (low speed of processing, low working memory, double deficit, and no deficit)?

When examining the results of this analysis, I am again faced with my very limited sample size. However, I was interested to see if students in each cohort displayed any specific "profile." In other words, do most of the students who have low processing speed also have low cognitive capacity and academic achievement? What about the students with low processing speed AND poor working memory? While I have examined this for the entire data set in research question one, I did want to look at each cohort separately.

For cohort one (low processing speed), several significant correlations were revealed. Of the fifteen comparisons, there is a significant correlation between:

- Speed of processing and quantitative aptitude
- Quantitative aptitude and verbal aptitude
- Quantitative aptitude and mathematics achievement
- Verbal aptitude and reading achievement

It is reassuring to see a correlation between the aptitude tests and their academic assessments; one would hope we would see strong correlation between a student's potential or aptitude in mathematics and how they perform on a math assessment. The same is true for the verbal aptitude and reading test. However, I am struck by the relationship between speed of processing and quantitative aptitude. This is the first of the analyses I have conducted which demonstrates a link between processing speed and intelligence. The data for the whole sample (n=72) did not reflect this relationship, but it is significant when looking at students with impaired processing speed. This may mean students with diminished processing speed might have lower aptitude in quantitative studies. However, as we know, correlation does not mean causation, so I make the statement with caution. While it is worthy of note, I do recognize the small sample size makes it difficult to draw any meaningful conclusions.

For cohort two (low working memory) I must point out the sample size was extremely small (n=12) so any conclusions are to be taken lightly. For this particular group of students, six of the fifteen pairs of assessments have statistically significant correlations. These are:

- Speed of processing and quantitative aptitude
- Speed of processing and verbal aptitude
- Speed of processing and math achievement
- Quantitative aptitude and verbal aptitude
- Quantitative aptitude and mathematics achievement
- Verbal aptitude and mathematics achievement

For this cohort of students, speed of processing becomes much more distinctly related to aptitude and achievement, although it is worth pointing out processing speed was not significantly correlated to reading achievement for this cohort either. As was explained in the meta-analysis by Breznitz (2005), students with poor working memory may be more dependent on processing speed because their working memory is not as robust. More specifically, if a student struggles to use their working memory efficiently, they must be able to process quickly before the information is lost to decay. If a typical peer can hold information for 20 seconds, they have 20 seconds to use that information and process it. However, if a student with impaired memory can only hold on to information for 10 seconds before it is lost, they may be able to "make up for" that deficiency via faster processing speeds.

For cohort three (double deficit in processing speed and working memory), six of the fifteen pairs assessment comparisons demonstrated statistically significant correlations. They were:

- Speed of processing and reading achievement

- Working memory and verbal aptitude
- Quantitative aptitude and mathematical achievement
- Verbal aptitude and reading achievement
- Verbal aptitude and mathematics achievement
- Reading achievement and mathematical achievement.

This analysis represents the only time processing speed and reading achievement have been significantly correlated. It is also the only time working memory has been significantly correlated with *any* of the assessments. Again, with such a small sample size, it is difficult to draw conclusions of much merit. However, it does mirror the findings of the Breznitz (2005) study; when a student has impaired processing speed and low working memory, a student cannot rely on either mechanism to compensate for the other. These students' cognitive resources are taxed to accurately and quickly identify letters and words, make sense of what they see and process that information. Teachers should be cognizant that students with this double deficit will need directions repeated more than once, and have access to them in multiple forms (verbal explanation as well as written.) These students will likely need reduced workload because the effort they will expend to answer one question may be equal to the effort a typical peer would use to answer seven. They will also benefit from frequent check-ins by the teacher to make sure they remember what they are supposed to be working on, and the steps they need to follow. These sorts of scaffolds will help double deficit students demonstrate their knowledge.

Even though students with impaired processing speed and low working memory face unique challenges, it is important to remember that from RQ4 analysis, this cohort did not score significantly lower than the other cohorts on any of the assessments, so despite having a double deficit, their results were not markedly different than their other peers.

For cohort four, students with no processing deficits, only one of the fifteen pairs demonstrated significant correlation:

- Quantitative aptitude and mathematical achievement

It is interesting to note this was the only correlation that emerged as significant in all four cohort groups. If nothing else, I can confidently say that the CogAT quantitative assessment and the MAP mathematics achievement test are highly correlated for this sample. Again, what is most interesting to me is that speed of processing was not significantly correlated with ANY of the assessments for this cohort. More to the point, fluctuations in processing speed did not seem to create fluctuations in capacity or academic achievement.

For the students with no deficit, I also found there was nearly no other significant association other than between quantitative aptitude and mathematics achievement. I find this odd. I had fully expected to see significant correlation between verbal aptitude and reading achievement as well. However, as I consider the referral process for this sample, perhaps it is this "oddity" that teachers also saw but could not explain. As explained earlier, all the students in the sample, including these with no apparent processing deficit, were brought forward by their homeroom teacher as needing additional diagnostic assessment. I think it is fair to say whatever the teachers were concerned about was not adequately assessed using these tests.

Rapid Automatized Naming (RAN) as a Measure of Processing Speed

As I have mentioned before, this study certainly has limitations, perhaps most notably, the small sample size. In addition, even though I wanted to measure students' speed of processing, the CToPP assessments only measured rapid automatized naming (RAN). One of the elements that makes my study unique is the use of RAN as a means of measuring processing speed. As mentioned in Chapter two, researchers use many different tools to determine processing speed, but RAN was not a common choice. This causes me to question whether what I am really looking at is not so much speed of processing, but rather speed of production—specifically linguistic production. Nearly all of the studies I reviewed measured processing speed based on reaction time, and very rarely was that reaction a verbal response. I do recognize the possibility I have not achieved a true measure of processing speed.

At this point, I stand behind my decision to use RAN as an indicator of processing speed. Fry and Hale (2000) define processing speed as "the rate at which an individual can complete basic cognitive functions such as naming or discriminating between familiar items" (p. 8). RAN is precisely the tool to measure the rate a student can name and discriminate familiar items. The CToPP test uses four different subtests for this naming, including letters, numbers, colors, and objects.

Again, some studies find a relationship connecting fluid intelligence and speed of processing (Catts, et al., 2002; Jensen, 1993; Kail, 2000). However, my results more closely align with the Conway et al. (2002) study, which suggested that when measuring processing speed with tools that "place minimal demands on memory and attention," (p. 178) processing speed does not significantly predict fluid intelligence. RAN tests are very simple and do not place inordinate demands on memory or attention; they are brief and ask students to name very common items. RAN is not a complex task, so it makes sense it might have a weak relationship with intelligence (Conway, et al., p. 180). Therefore, if speed does not predict intelligence, my results corroborate this theory. More specifically, RQ2 demonstrated no significant correlation between processing speed and verbal or quantitative aptitude. While Fry and Hale (2000), Catts et al., and Kail (2000), demonstrated different findings, my results most similarly align with Conway et al. Regarding the research about mathematical aptitude and achievement, my results did match those of Raghubar, et al. (2010) in that the students with low working memory also demonstrated lower mathematics achievement.

Although my results did not match all of his findings, another example of this study's results aligning with prior research is with the theories from Arthur Jensen. Essentially, Jensen (1993) suggests if an individual processes slowly, there is increased potential for incorrect responses, poor reasoning and less overall knowledge acquisition. This could be the reason for the results in RQ3. Slower processing students in my sample did not do as well on the achievements tests, despite a lack of correlation between speed and aptitude and this could be because of what Jensen suggests.

Recommendations for Future Research

As is often the case with research, I have many unanswered questions. One of the pieces that is missing from this study is a conversation with students who match the profiles I have studied. It would be powerful to include a qualitative analysis that provides the thoughts, experiences, and feelings of the students who I have been studying. I would like to know what *they* think they need to be successful; what have teachers done that made learning easier? What have they experienced that created a hardship at school? How do they think they learn best? Answers to these questions could dramatically inform teaching practices, which would potentially improve student learning.

I also noted a gap in the literature and research using same age students. While this study does contribute to closing that gap, it is not enough, especially given my small sample size. Additional research needs to be done using same age students, and preferably following their progress over time. The cascade effect, if true, makes it very difficult to draw conclusions when looking at a mixed age sample.

Finally, I think it will be important to tap into the most current research about the human brain. There is extensive study and literature using functional magnetic resonance imaging (fMRI) that is dramatically changing the way we think about learning and the brain. While I am not an expert on the biochemistry or neurological anatomy of the brain, it would be fascinating to be able to "see" the differences between a slower processing brain compared to a faster processing brain. More importantly, we could start to address the question about whether or not we can improve processing speed, and if so, do those improvements last over time?

Recommendations for Practice

At the outset of this research, one of my goals was to provide teachers, administrators, and parents with instructional recommendations for students with low processing speed. Knowledge without action can be meaningless, and I do not want these findings to go unaddressed.

In my building and as the principal, I have the advantage of a captive audience. I plan to share these findings with my staff, and engage in a conversation about our slower processing students. I want to make it very clear that teachers have permission to do things differently for their students who learn and think differently. I want them to know that fair does not always mean equal. This is true for *all* students, not just those with impaired processing speed.

More specifically, I plan to share the following ideas about how we can help students with impaired processing be more successful at school:

- Provide a "heads-up" – tell the student that in a few minutes you are going to ask them to share what they know about a certain topic. Give them a few minutes to organize their thinking before asking them to talk in front of their peers.

- Do not assume they are being lazy. When you have asked students to start an assignment, the slow processor is going to need TIME to think before they jump in and start working. Grant them this time.
- For writing assignments, allow the slower processing student to talk out loud about what they are going to write before they begin. Capture their thoughts on paper and give it back to them when they are done. This will help facilitate timely production of work.
- Ask the students about the connections they see between and across subjects. Slower processing students can make remarkable connections that others may not notice.
- Consider reducing homework and general workload. If a student can demonstrate their knowledge of a topic or concept in a few problems, the repetition is not always beneficial for a slow processing student.
- Remember, the evidence suggests that slower processing students are as bright and capable as their peers – treat them that way!

Conclusion

And so, after all the analysis and research and findings, I am left with a fundamental question: what can I do with this information? I agree with the American Psychological Association's stance: "To base a concept of intelligence on test scores alone is to ignore many important aspects of mental ability" (American Psychological Assicoation, Inc., 1996, p. 79). My students are more than their test scores—they are future leaders, teachers, doctors, and business executives. As the APA report captures so eloquently:

> group means have no direct implications for individuals. What matters for the next person you meet (to the extent that test scores matter at all) is that person's own particular score, not the mean of some reference group to which he or she happens to belong. (p. 90)

I simply could not agree more. "In the case of intelligence test scores, the variance attributable to individual differences far exceeds the variance related to group membership," (American Psychological Assicoation, Inc., 1996, p. 91) thus, my results are interesting, but not as important as a student's individual scores and experiences.

Homeroom teachers selected members of this sample group for additional assessment. Their inclusion was not arbitrary or capricious; rather the teachers saw evidence of a "disconnect" between these students' ability and performance. Future research in this area will need to include a qualitative component where researchers talk with individual students about their school experience. It will be important to hear their impressions regarding what helps them succeed and what may impede their performance. As I suggested at the beginning of this study, my belief is students with lower processing speeds have an internal metronome set to a beat slightly slower than the rest of us. They move a little slower, think a little longer, want to pause before answering, and prefer to hear other's responses before positing their own. I believe they are bright, worthy, incredible people who are not enjoying school because they constantly feel left behind by their peers and teachers. The conveyor belt is set at a fast walking pace for most of our kids, but for students with lower processing speeds, it might feel like a dead sprint. No one can keep up at that pace for very long.

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