

**UNDERLYING COGNITIVE PROCESSES IN READING, MATH, AND COMORBID  
READING AND MATH LEARNING DISABILITIES**

by

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## ABSTRACT

The performance of 223 Grade 4 children, with Average overall IQ and no disability (ND), or reading disability (RD), or math disability (MD), or reading/math disability (RD+MD), was compared on theoretically-derived factors measuring specific cognitive processes underlying reading and math achievement. The processes included automatic visual/orthographic and visual/math fact retrieval, working memory span, phonological and algorithmic processing, and IQ (e.g., verbal/nonverbal reasoning). Good readers and good mathematicians (ND group) showed solid performance across all tasks. Compared to the ND group, achievement and cognitive profiles of single disability (RD and MD), and RD+MD were elucidated. Structural equation models (SEM) for the entire sample confirmed a theoretically-derived four factor READ model and a four factor MATH model, both with identical Working Memory Span and IQ factors. Two other READ model factors were Automatic (RAN/Words) and Phonological Processing. Two additional MATH model factors were Automatic (RAN/Facts) and Algorithmic Processing. Based on the cognitive and functional neurobiological literatures, these models supported a systems view of the unique and collaborative relations among the automatic, processing, working memory, and IQ cognitive processes underlying reading and math achievement. Through regression analyses, the specific factors from both the READ and MATH models predicted each group's reading and math achievement. Regression results enhanced our understanding of what factors/cognitive processes (strong or weak) contribute to good or poor reading and math achievement. Findings that automatic RAN/Words and RAN/Facts both predict fluent math fact retrieval for all groups suggest potential overlap in basic automatic visual/orthographic and visual/fact routes. Possible overlap in these automatic processes was also seen in the weakest RD+MD group for word reading.

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## INTRODUCTION

Learning disabilities in reading and math impact the lives of many individuals. Lyon (1996) documented that 80% of learning disability (LD) diagnoses are later revealed to be reading disabilities (RD). With regards to the prevalence of the various LDs, Snowling (2000) reported that 5 % of school-aged children have reading disabilities (RDs), or dyslexia, and Geary (2004) documented that 5 - 8 % of children have an arithmetic disability (AD) (i.e., math disability [MD]). Comorbid reading and math disabilities (RD+MD) are also frequently documented. It has been reported that 40-60% of children with primary RDs have comorbid MDs (Badian, 1982; Geary, 1993) and 17% of children with primary MD have a comorbid RD (Gross-Tsur et al., 1996). Badian (1999) assessed reading and arithmetic achievement in 1,075 children from Kindergarten up to the end of Grade 7 or 8. Approximately 2.3% of this population had a MD, 6.6% had a RD, and 3.4% had a comorbid RD+MD. Less research has been reported for children with MD or comorbid RD+MD, than for children with RD only (Badian, 1999; Geary, Hoard & Hamson, 1999).

The literature on children with single RDs or MDs documents several different cognitive processing deficits. The present research focuses on the major processing deficits that appear to overlap and that account for much word reading and math calculation difficulties. These include automaticity (i.e., accuracy and rate for word reading or math facts), processing (i.e., phonological or algorithmic), and working memory span (i.e., the ability to hold verbal/phonological and visual information online for further manipulation). The little research that does exist on children with comorbid RD+MD suggests that they have a more severe combination of the underlying single RD and MD deficits. In the current study the cognitive profiles of children with average overall IQ and no disability (ND), single

RD or MD, and comorbid RD+MD are investigated to further understand the unique and possibly shared cognitive deficits in single and comorbid disability groups. Assessing the unique and shared underlying cognitive processing deficit(s) associated with reading, math, or comorbid reading/math disabilities may help to guide diagnoses and special education programming.

### Cognitive Processes in Reading

Specific deficits in cognitive processes are discussed in the reading literature as contributors to RDs. These include deficits in automatic visual/orthographic retrieval and phonological processing. We refer to visual/orthographic retrieval as the automaticity (i.e., accuracy and fluency) with which one can rapidly name text-based information (e.g., Rapid Automatized Naming (RAN) for letters and digits) and read whole words without needing to rely on phonological decoding processes. Phonological processing refers to the application of phonological awareness skills when using grapheme-phoneme conversion and blending to ‘figure out’ or decode an unfamiliar word.

Neuropsychological research originally focused on apparent visual-verbal disconnections in brain injured individuals who exhibited deficits in RAN speed (Denckla & Rudel, 1976). Neuropsychologists later proposed two possible routes to reading. More specifically, individuals with brain damage affecting the visual-orthographic route had deficits in whole word reading with seemingly intact phonological processing (i.e., surface dyslexia); whereas individuals with brain damage affecting the phonological decoding routes showed the opposite pattern with intact whole word reading and deficits in phonological processing (i.e., phonological dyslexics) (Castles & Coltheart, 1993; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Castle, Perry, Langdon, & Ziegler, 2001). While later

research did not reliably support a mutually exclusive dual route model, considerable cognitive, developmental, and neuroimaging research supported the relative independence and collaboration of these two access routes in word reading. These results suggested another possible area of deficit for children with RD, namely the visual/orthographic-phonological connection.

Seemingly the visual/orthographic-phonological connection would require a cognitive work space (i.e., working memory) in order to pool together familiar and unfamiliar word parts in order to apply phonological processing skills to read a new or unfamiliar word. A boom in research into the frontal lobe systems, associated working memory span (i.e., holding and manipulating information in verbal or visual working memory for further manipulation), and executive function led to investigation into the contribution of working memory to reading (Bradley & Bryant, 198; Gathercole, Willis & Baddeley, 1991; Hansen & Bowey, 1994; Leather & Henry, 1994; McDougall, Hulme, Ellis & Monk, 1994; Rohl & Pratt, 1995). Research investigating the degree of independence and collaboration of the visual/orthographic and phonological processing routes, and working memory span's integrative role in the visual/orthographic-phonological connection, is summarized below.

#### Automatic Visual/Orthographic Route

The visual/orthographic processing component of reading has been researched less than the phonological processing component (Bell, McCallum, & Cox, 2003). However, research findings do show that deficits with visual orthography characterize some of the RD population (Bell & Worthington, 2002; Hultquist, 1997). The 'cross-modal' hypothesis or 'paired associate learning deficit' (Plaza & Cohen, 2005) suggests that some children with RDs have deficits in associating verbal labels with visual stimuli that may be independent of

any phonological awareness problems (Mayringer & Wimmer, 2000; Windfuhr & Snowling, 2001; Plaza & Cohen, 2005)

Based on RAN findings, Denckla & Rudel (1976) proposed a 'visual-verbal disconnection syndrome' in which weak automatic retrieval of names, via visual-verbal association, was faulty in brain injured and dyslexic (i.e., RD) children. Wolf et al., (2000, 2002) proposed a temporal sequence of cognitive processes associated with rapid naming, including: 1) perceptual recognition; 2) lexical processes: word retrieval, and 3) motor processes: articulation. Deficits in rapid naming were not found to be associated with difficulties in articulation rate, short-term memory, or visual scanning (Bowers, Steffy & Tate, 1988; Obregon, 1994; Wimmer, 1993). Core weakness in children with RD appears to be with the second part of the process, namely the lexical access needed to automatically name letters (RAN: L), digits (RAN: D), and words from long-term memory (see Bowers & Ishaik, 2003).

A deficit in naming is strongly related to the inability to quickly retrieve words based solely on their visual form/orthography (Wolf, Bally, & Morris, 1986) and is a good predictor of weak reading accuracy and poor reading comprehension (e.g., Bowers & Wolf, 1993; Wolf, 1991; Wolf & Bowers, 1999; Wolf, Bowers & Biddle, 2000; Young & Bowers 1995). A reliable relation between reading fluency and rapid automatized naming tasks (e.g., RAN) has also been demonstrated (Levy, Abello, & Lysynchuk, 1997). Poor readers are generally slower than average readers when reading words in isolation (e.g., Ehri & Wilce, 1983) and experience difficulty reading irregular/exception words (Lovett, 1987; Manis & Morrison, 1985; Seidenberg, Bruck, & Backman, 1985). Mayringer and Wimmer (2000) suggested that the slow speed with which they read impedes their access to the orthographic

form of words. Furthermore, reading irregular or exception words in English (e.g., Lovett, 1987) forces lexical access through a visual/orthographic route, as these words cannot accurately be sounded out in their entirety using English language grapheme-phoneme conversion rules (e.g., ‘yacht’ ‘have’). Since many poor readers cannot access this route in an efficient manner, this helps account for the difficulties they experience reading irregular/exception words.

Pseudowords are nonwords that contain high frequency spelling patterns in written English and are designed to test phonological decoding, separate from visual/orthographic skill. Booth, Perfetti, MacWhinney, and Hunt (2000) showed that rapid auditory perception accounted for unique variance in pseudoword reading and not in irregular words, while rapid visual perception accounted for variance in irregular words and not in pseudowords. Manis et al. (2000) assessed the amount of variance RAN letters and phonological awareness accounted for when predicting irregular and pseudoword reading. They found that while both processes were important predictors of both types of word reading, RAN letters accounted for more unique variance in irregular than in pseudoword tasks, and that phonological awareness accounted for more unique variance in pseudoword than in irregular word tasks. In terms of pathways, this suggests that reading irregular and pseudowords both require access to visual/orthographic and phonological processing routes, with the visual/orthographic route being accessed more for irregular words and the phonological processing route for pseudowords.

#### Phonological Processing: Awareness and Decoding

Phonological awareness, or recognizing the sounds of language, is an important component of phonological processing (Siegel, 2003). Phoneme awareness develops as

reading skill progresses (Vandervelden & Siegel, 1995). Phonological awareness tests typically assess the ability to identify individual phonemes in spoken words and/or nonwords and then manipulate these phonemes by adding, removing, substituting, and/or moving a sound to create a new word. Other phonological awareness tests include identifying rhymes and reading nonwords. Deficits in phonological awareness are found to be a major contributor to reading failure (e.g., Bradley & Bryant, 1983; Fletcher et al., 1994; Mann, 1984; Shankweiler et al., 1995; Siegel, 2003; Stanovich & Siegel, 1994). Poor readers show weaker phonological awareness as exemplified by their difficulties segmenting and deleting phonemes from words (Pratt & Brady, 1988). Compared to age-matched average readers, many poor readers demonstrate weaker phonological awareness on sound categorization tasks (Bradley & Bryant, 1983). These tasks also discriminate poor readers from younger reading-matched controls (e.g., Duncan & Johnston, 1999; Fawcett & Nicholson, 1995). Bruck (1992) matched children with RD with both age- and reading-matched controls and found that the RD group performed the lowest among these groups on a phoneme deletion task.

Core deficits in children with RD are regularly found in their phonological awareness and phonological processing skills (Brady & Shankweiler, 1991; Catts, 1989, 1996; Fletcher et al., 1994; Stanovich & Siegel, 1994; Wagner & Torgeson, 1987; Wolf & Bowers, 1999). Within the context of word reading tasks, phonological processing is related to the ability to apply grapheme-phoneme correspondences to accurately decode parts of a word in order to blend and read the whole word form. Deficits in phonological processing are associated with difficulties in learning to read (Fawcett, 2001; Hulme et al., 2005; Share, 1995; Snowling, 2000; for reviews). There is consensus that phonological processing, in the English

language, uniquely predicts reading achievement in good and poor readers (Adams, 1990; Badian, 1998; Ball & Blachman, 1991; Floorman, Francis, Shaywitz, Shaywitz, & Fletcher, 1997; Wagner & Torgeson, 1987). Research also shows that RD children have deficits in pseudoword reading, highlighting weaker phonological decoding skills (Bruck, 1988; Siegel & Ryan, 1988; Waters, Bruck, & Seidenberg, 1985).

### The Orthographic--Phonological Processing Connection

A dissociation between word retrieval that relies mostly on visual/orthographic route (e.g., yacht), and pseudoword retrieval that depends heavily on the phonological processing system (e.g., manta) may appear independent; however, cognitive, developmental, and neuropsychological research along with results from effective remediation (Lovett et al., 2000a; Lovett, Steinbach, & Frijters, 2000b) suggest a dynamic integration and feedback loop whereby the orthographic/visual and phonological routes work in partnership. Gough and Juel (1991) reported a correlation of .55 between reading pseudowords and real words, and Siegel and Ryan (1988) reported a correlation of .86.

In the initial stages of reading acquisition, letter knowledge is pertinent. Letters each have their own sound correspondences and are in effect pseudowords--or novel phonemic units (Share & Stanovich, 1995). The sequential processing involved in grapheme-phoneme conversion leads to an increase in orthographic representation (Adams, 1990; Ehri, 1992). However, deficits in either the orthographic or phonological systems have been shown to be strongly associated with difficulty storing and retrieving sight words and learning different grapheme-phoneme combinations (Gathercole & Baddeley, 1989, 1990a, 1990b). Visual/orthographic and phonological processing both contribute significantly and reciprocally to reading accuracy and decoding success (e.g., Bryant, MacLean, Bradley, &

Crossland, 1990; de Jong & Van der Leij, 1999), even when the influence of IQ and memory are controlled (Bradley & Bryant, 1985). As children acquire phonological processing skills (e.g., awareness and decoding), more complex orthographic structures can be decoded. With further consolidation between visual orthographic-phonological connections, whole words can be read more automatically or fluently (Ehri & Wilce, 1983; Share, 1995, 1999; Stuart & Masterson, 1992).

The amount of variance that is associated with naming via a visual/orthographic route versus a phonological processing route, and the impact of deficits in one or both routes on word reading have been the focus of many studies. At various ages, RAN (a representative of the visual/orthographic route) has consistently been found to contribute unique variance to reading, over and above phonological awareness (Bowers, Steffy, & Swanson, 1986; Schatschneider, Carlson, Francis, Foorman, & Fletcher, 2000; Wolf, 1999). Wolf and colleagues have defined ‘double deficit’ subgroups, with deficits in both naming speed and phonological awareness, and these included the most severely reading disabled (Wolf, 1999; 2002; Wolf, Bowers, & Biddle, 2000; for review, see Bowers & Ishaik, 2003). Lovett (1987) compared rate disabled and accuracy disabled groups; she found that the rate disabled readers had deficits in RAN alone, while the accuracy disabled group demonstrated both RAN and phonological awareness deficits.

Which route is employed also depends on who is reading--good or poor readers? young or mature individuals? Bowers (1993) showed RAN to be highly related to the speed of reading text in both poor and good readers’, above and beyond any relation to phonological awareness. Research shows that poor readers reading is best predicted by their performance on RAN and phonological awareness tasks, while good readers rely on more

advanced phonological decoding strategies (e.g., McBride-Chang & Manis, 1996; Meyer, Wood, Hart, & Felton, 1998). Looking at the development of the visual/orthographic-phonological connection, Backman and colleagues (1984) found early readers to use an orthographic route for high-frequency words while learning grapheme-phoneme patterns. Wagner et al. (1994, 1997) found that RAN contributed significant unique variance to the reading performance of children in Kindergarten up to the end of Grade 2, while phonological awareness also contributed variance to the reading performance of older children, up to the end of Grade 4.

Studies comparing phonological and orthographic awareness (e.g., tasks requiring the choice of the correct spelling) in ND and RD children suggested that children with RDs showed relatively better developed orthographic awareness and deficits in phonological processing and working memory (see Siegel, 2003 for review). While these findings have been used to suggest that children with RDs have an intact visual/orthographic route, it is noteworthy that these studies used higher frequency spelling patterns on orthographic awareness tasks. This finding may have over-interpreted to suggest that the poor readers may have had intact orthographic awareness that they relied on, but these tests did not require knowledge of more advanced orthographic patterns (e.g., lower frequency, and irregular/exception words). Siegel (2003) reviewed orthographic and phonological processing deficits in early and poor readers. Both early and poor readers experienced difficulty matching the visual form of a pseudoword that they heard and reading orthographic spellings with multiple phonemes (e.g., ‘ose’), vowels, consonant blends, exception words, low frequency regular words, pseudowords as the number of syllables increased, and high frequency words but not their matching pseudoword (e.g., ‘**ran**’ versus ‘**han**’) (for review,

see Siegel 2003). It appears that poor readers do not have complete failure of the visual/orthographic route, but rather a less developed route that is less capable of automatically retrieving more complex orthographic and phonemic patterns. Furthermore, their phonological processing route may also be underdeveloped or impaired and characterized by limitations in working memory capacity.

In addition to which route is relied on more in RDs and whether it is one or both, temporal sequencing of information also impacts how automatically/rapidly a word is read. Breznitz (2002) linked the temporal, visual-verbal, and cross-modal hypotheses, proposing that discrimination and identification are faster via the visual than auditory route. Breznitz posits that speed-of-processing deficits affect the connection between the visual and phonological routes that underlie reading deficits (Breznitz, 2002). Others argue that automaticity of the orthographic-phonological system is critical to an adult reader's rapid word naming, as noted to be housed in the Visual Word Form Area (VWFA) in the left ventral-posterior neural system of the brain (Cohen et al., 2002; Lukatela & Turvey, 1994; Perfetti & Bell, 1991; McCandliss, Cohen, & Dehaene, 2003). When unfamiliar words are encountered, the two systems work together using automatic orthographic recognition (e.g., sight words) for familiar parts of the word, and phonological processing strategies, to help the unfamiliar become familiar. It is proposed that the working memory span (i.e., the ability to manipulate information using verbal rehearsal and/or visualization) is employed to hold the automatic/familiar and unfamiliar online long enough so that phonological processing can occur.

## The Visual/Orthographic-Phonological Connection and the Integrative Role of Working Memory

Working memory has been defined as a system of limited capacity for storing and manipulating temporary information that is held in short-term memory (McLean & Hitch, 1999). The phonological loop, visual sketch pad, and executive system of Baddeley and Hitch's (1974) working memory model appear to all be important in the acquisition of reading (Bull, Johnston, & Roy, 1999; Heathcote, 1994; Logie & Baddeley, 1987; Logie, Gilhooly, & Wynn, 1994). According to Baddeley and Hitch's working memory model, short-term memory storage can be provided by one of two slave systems: 1) the articulatory/phonological loop or 2) the visual-spatial sketchpad. The phonological loop supports the verbal rehearsal processes involved in articulation and phonological manipulation (Logie & Baddeley, 1987). The visual-spatial sketchpad supports manipulation of the orthographic or visual component of phonemes (Heathcote, 1994). Finally, the executive system allocates attention and coordinates the order of the necessary operations (Bull et al., 1999).

Citing many studies, Plaza and Cohen (2003) proposed that phonological processing not only involves phonological awareness of the speech sound structure of the language, but also retrieval of phonological information from long-term memory, and phonological encoding of information into working memory (Bryant, Nunes, & Bindman, 1998; Crain, Shankweiler, Macaruso, & BarShalom, 1990; Gathercole & Baddeley, 1990; Morris et al., 1998; Snowling, Hulme, & Goulandris, 1994; Wagner, Torgeson, & Rashotte, 1994). There is also evidence that the pattern of variance accounted for in reading achievement by rapid naming, phonological awareness, and verbal-working memory changes across the

developmental span (De Jong & van der Leij, 1999; Wagner, Torgeson & Rashotte, 1994; Wagner et al., 1997).

Many studies have supported the collective contribution of phonological awareness and verbal-working memory to reading achievement (Bradley & Bryant, 198; Gathercole, Willis & Baddeley, 1991; Hansen & Bowey, 1994; Leather & Henry, 1994; McDougall, Hulme, Ellis & Monk, 1994; Rohl & Pratt, 1995). Snowling et al. (1996) followed a group of 20 phonological dyslexics (mean age = 9.67 years) and a group of reading-matched controls and found that the RD children with mainly phonological deficits (i.e., phonological dyslexics) performed more poorly on both phonological processing and verbal short-term memory tasks (Fowler, 1991; Snowling et al., 1994). Research also shows that poor readers exhibit a reduced working memory span for verbal material (e.g., letters, digits, word strings, and phonological processing) (Baddeley, 1986; Holligan & Johnston, 1988; Rapala & Brady, 1990).

Phonological processing deficits have been further associated with poorer performance on working memory digit span tasks, phonological awareness and phonological (working) memory tasks (e.g., Brady & Shankweiler, 1991; Gough, Ehri, & Treiman, 1992; Stanovich, 1991, 1994; Wagner & Torgeson, 1987). It has been proposed that working memory and phonological awareness develop in parallel (Naslund & Schneider, 1996). Remedial training of phonological awareness deficits enhances performance on phonological awareness tasks *and* working memory processes (Brady, Fowler, Stone, & Winbury, 1994; Ellis, 1990). Further evidence that phonological awareness and working memory tasks are highly related is found in research that working memory tasks do not contribute unique

variance in reading beyond that contributed by phonological awareness (DeJong & van der Leij, 1999).

In the present study, it is proposed that when a sight word is familiar (e.g., ‘cat’ or ‘pill’) it can be read automatically, in its entirety, through a visual/orthographic-route. If an unfamiliar word (e.g., ‘caterpillar’) requires reading, the executive system employs working memory span as an integration system that holds (through verbal rehearsal and/or visualization) the automatically familiar sight words ( e.g., ‘cat’ and ‘pill’) and unfamiliar phonemes (e.g., ‘er’ and ‘ar’), in their appropriate sequence, so that phonological processing of the larger words elements can occur simultaneously. Thus, when unfamiliar words are encountered, the two systems can work together in a dynamic partnership by holding already fluent orthographic patterns (e.g., sight words) and graphemes online in working memory to employ phonological processing strategies to integrate information from the two routes.

#### Functional Neurobiological Processes Underlying Cognitive Processes in Reading

A recent body of fMRI research is summarized to demonstrate the similarities in automatic/visual retrieval, phonological processing, working memory, and executive neurological systems that potentially ‘room with’, or are neighbours with, each other in functional neurobiological systems in the learning brain. Research using functional magnetic resonance imaging (fMRI) to investigate reading development and RD report congruent findings on the neural architecture in ventral areas associated with automatic/orthographic processing, frontal regions associated with phonological processing, and dorsal regions associated with the orthographic/ phonological integration systems in reading (for reviews, see Eden & Zeffiro, 1998; Pugh, Mencl, Jenner, et al., 2000; Sandak, Mencl, Frost, & Pugh, 2004; Sarkari et al., 2002; Shaywitz & Shaywitz, 2003).

For example, Logan's (1988, 1997) word analysis system consists of two parts: an 1) automatic rapid whole word (i.e., orthographic) system that has been related to activation of the ventral-posterior neural system, including the left hemisphere middle occipitotemporal/fusiform area, and greater left (than right) lateral extrastriate activation (Pugh et al., 1996), termed the Visual Word Form Area (VWFA) (Cohen et al., 2002; McCandliss, Cohen, & Dehaene, 2003) and OT skill zone by Sandak (2004); and a 2) phonological processing, and sub-lexical speech system, that processes word parts more slowly and has been associated with activation in the frontal neural system, including the inferior frontal gyrus (IFG) (e.g., Demone et al., 1992; Zattore, Evans, Meyer, & Gjedde, 1992) and the dorsal posterior regions of the inferior frontal cortex (IFC) (Poldrack et al., 1999). A third dorsal temporoparietal posterior system has been associated with integrating orthographic and phonological processing (Price et al., 2000; Pugh et al., 2000; Booth et al., 2004). It includes the angular gyrus (ANG), supramarginal gyrus (SMG), posterior superior temporal gyrus (PSTG) or Wernicke's area (Misra, Katzir, Wolf, & Poldrack, 2004) and inferior parietal lobule (IPL). Increasing fMRI evidence during specific reading tasks supports this triple system model (for review see, Pugh et al., 2005).

### Cognitive Processes in Math

Specific deficits in cognitive processes are discussed in the math literature as contributors to MDs. These include deficits in visual/math fact retrieval and algorithmic processing. The present study proposes that automatic (i.e., accurate and fluent) visual/math-fact retrieval occurs when an answer to a math fact (e.g.,  $2 + 2 = 4$ ) is directly retrieved, without needing to apply algorithmic processing. Algorithmic processing refers to the

manipulation of unknown parts of math facts, and the application of calculation rules and procedures, in order to solve the whole algorithm.

Early neuropsychological research into the etiology of MD (called dyscalculia in the neuropsychological literature) reported a potential dissociation between arithmetic facts (e.g.,  $6 + 6$ ) and arithmetic procedures (i.e., algorithmic processing). McCloskey and colleagues (McCloskey, 1992; McCloskey, Caramazza & Basili, 1985) developed a hierarchical model that suggested two distinct processes: 1) Number processing, and 2) Calculation. It has been proposed that deficits in either of these systems can result in a dyscalculia for number processing (Pesenti, Thioux, Seron & De Volder, 2000), retrieval of arithmetic facts (Pesenti et al. 2000) and/or calculation procedures (Temple, 1989, 1991; 1992; 1994). Geary (2004) later suggested that a semantic memory math disability was reflected by inaccurate and variable response times for math fact retrieval, while a procedural math disability resulted in procedural errors in calculations (e.g. errors in carrying or borrowing). At the time, Geary (2004) reported that the relation between a procedural math disability and a reading disability was unclear.

Similar to the reading research outlined above, research on math processing has suggested a visual/math fact retrieval route, an algorithmic processing route, and connection between the two routes. The relative independence and collaboration of these two access routes to solving math calculations is explored in the current research study. The present study will extrapolate from research in the reading domain into research in the math domain, to explore the possible similarities between proposed automatic visual/orthographic and automatic visual/math fact retrieval routes (i.e., the phonological and algorithmic processing routes, and the integrative role of working memory in both).

### Automatic Visual/Fact Route

Compared to the reading domain, less literature exists on arithmetic development. Speeded tasks that appear related to math achievement in children include counting rate (i.e., articulation) and rapid naming of digits (e.g., RAN digits) (Denckla & Rudel, 1976; Wolf, 1991). Geary (2004) cited many studies in which children with MD had significantly weaker automatic retrieval of basic math facts (Barrouillet et al., 1997; Bull & Johnston, 1997; Garnett & Fleischner, 1983; Geary, 1993; Geary & Brown, 1991; Geary et al., 1987; Jordan & Montani, 1997; Ostad, 1997). Hitch and McAuley (1991) suggested that children with MD showed a lack of automaticity in retrieving numbers and number combinations from long-term memory.

After controlling for reading ability in 7-year olds, Bull and Johnston (1997) found that arithmetic ability was best predicted by processing speed via a visual route (e.g., visual number matching task) with no other cognitive process contributing to further unique variance. These authors suggested that a general speed-of-processing deficit might underlie children's difficulties with automatizing basic arithmetic facts. They also reported a significant correlation between math and reading achievement ( $r = .67$ ) (Bull & Johnston, 1997).

In the present work, it is hypothesized that similar to deficits in the automaticity of the visual/orthographic naming route in children with RD, children with MD present with a deficit in accessing the visual form of numbers and automatically retrieving their associated answer (e.g.,  $1 + 1 = 2$ ;  $2 + 2 = 4$ ). While Geary termed the retrieval of automatic math facts a phonetic-semantic memory system, here it is proposed that the automatic visual- (orthographic or fact) system reads the word, or answer to the fact, automatically as a whole,

prior to the semantic relation (i.e., the meaning of the word or fact) to the answer being accessed. This study focuses on the automatic visual/fact route for math fact retrieval, and not on a phonetic-semantic one. The role of semantics (i.e., meaning) of words and facts is a large issue beyond the scope of the current study.

### Algorithmic Processing and Working Memory

In the reading literature, phonological processing (i.e., awareness and decoding) was investigated at length prior to recent research on working memory. In the math literature, the role of algorithmic processing and working memory were investigated concurrently and, hence, are discussed together in this section.

In the math domain, working memory has been strongly associated with arithmetic tasks such as counting procedures, solving simple addition facts, and working through more difficult word problems (Adams & Hitch, 1997; Geary, 1990; Geary & Widaman, 1992; Logie, Gilhooly, & Wynn, 1994). Klein and Bisanz (2000) reported that preschoolers' accuracy on simple addition and subtraction problems was strongly associated with the number of units that the child had to hold in working memory. It has been reported that children with arithmetic difficulties demonstrate a deficit in holding numbers in short-term memory on tasks such as Digit Span Forwards (WISC-III) and Counting Span (Siegel & Ryan, 1989). Bull and Johnston (1997) reported that short-term memory and verbal working memory predict Grade 3 and 4 children's ability to solve multi-digit algorithms. Thus, working memory deficits can also impair multistage computation (e.g.,  $253 + 528 + 124 + 351$ ) (Geary, 1993).

Working memory deficiencies have consistently been shown to be associated with MDs (Geary 1990, 1993, 2004). Children with MD have significant working memory

weaknesses, as seen in their trouble maintaining information in the articulatory or visual-spatial working memory systems ( Hitch & McAuley, 1991; McLean & Hitch, 1999; Siegel & Ryan, 1989; Swanson, 1993). In the MD population, Geary (2004) suggested that using finger counting as a memory aide, instead of direct retrieval, could be associated with working memory difficulties. Hitch and McAuley (1991) showed that children with MDs had a deficit on long-term memory tests but demonstrated good articulation rate. Poor working memory resources have, in turn, been proposed to lead to poor representation of arithmetic facts in long-term memory (Geary 1990; Geary, Bow-Thomas, & Yao, 1992; see review by Geary, 2004)

Geary and his colleagues have argued that differences in performance between ability and disability groups on ‘sequential’ mental addition problems (e.g.,  $2 + 4 + 5 + 7 =$ ) parallel differences in working memory (Geary, 1996; Geary, Bow-Thomas, Yao, 1992; Geary & Brown, 1991). They suggest that differences in working memory resources may be the reason for differences on many arithmetic calculations, including counting knowledge, counting strategies, and deficits in retrieval strategies for automatic number facts (e.g., addition). Thus, children with a competent working memory system should show a higher level of automatization of facts, as has been evidenced by a quicker and more accurate level of retrieval from memory (Janssen et al., 1999).

It has been proposed that these children do not develop long-term memory representations for automatic number facts because the information that is necessary to do so does not stay in working memory long enough to be consolidated. However, if this was the case, ability-matched controls should perform better on all working memory tasks in comparison to arithmetic disabled children, and this is not the case (McLean & Hitch, 1999).

To help explain this, we propose that deficits in one or both of the automatic visual/fact retrieval routes and in working memory span can negatively impact performance on arithmetic calculations. For example, to solve  $2 + 4 + 7 =$ , first the automatic math fact (e.g.,  $2 + 4 = 6$ ) could be retrieved from long-term memory via a visual/fact route, and held in working memory (either verbally and/or visually-depending on the child) in order to apply more advanced algorithmic processing strategies (e.g.,  $6 + 7 =$  ‘I know  $5 + 5 = 10 + 3 = 13$ ’) to solve unfamiliar (i.e., less automatic) sequential math problems.

McLean and Hitch (1999) suggested that the consistent finding of no difficulties with the manipulation of phonemes in the phonological loop, but significant deficits in Digit Span in children with MD, is suggestive of a specific deficit remembering numerical stimuli. In other words, a short-term memory problem that, in turn, stunts working memory is suggested.

#### The Visual/Math Fact-Algorithmic Processing Connection and the Integrative Role of Working Memory

Similar to high frequency letter-sound patterns to read whole words and increase automaticity, the faster that one retrieves basic math facts (e.g., addition facts such as  $2 + 2 = 4$ ), the faster one can complete an addition algorithm (e.g.,  $23 + 23 =$  automatic  $3 + 3 = 6$  and  $2 + 2 = 4$ ). Kail (1992) maintained that retrieving facts quickly and automatically frees up processing/memory resources and allows for more advanced operations to occur (e.g., algorithms like  $423 + 8423$ ). In support of this hypothesis, children demonstrated a strong association between their ability to recall automatic facts for an operation (i.e., simple addition) and their ability to perform algorithmic calculations for that same operation (Case, Kurland, & Goldberg, 1982).

When a fact or word is unfamiliar, the visual-naming system automatically identifies what it can, while the advanced processing system (phonological or algorithmic) identifies unknown parts. The two then pull together what they know 'online' into working memory using either a verbal rehearsal (i.e., phonological loop) or a visualization strategy (i.e., visual-spatial sketchpad) to ultimately integrate what they know. This should be an efficient system in good readers and good mathematicians, a system that works toward enhancing their knowledge of new words and facts and increasing their automatic access through a visual route. Geary's Response Time (RT) studies showed that good second grade mathematicians used a more advanced counting-on strategy (e.g.,  $3 + 4 = '4,5,6,7'$ ), while poor Grade 3 mathematicians used a less advanced strategy of counting--all (e.g.,  $3 + 4 = '1,2,3,4,5,6,7'$ ). Geary (2004) reported a similar pattern when children with MD solved subtraction facts (e.g., Ostad, 2000). Geary (2004) outlined two additional strategies that came after counting on. These were retrieval, where the answer to the whole fact was retrieved automatically (e.g.,  $3 + 4 = '7'$ ), and decomposition, where part of the sum was retrieved, followed by counting-on (e.g.,  $3 + 4 = '3 + 3 = 6 \text{ plus } 1 = 7'$ ).

It is proposed that, similar to the orthographic-phonological connection in reading, a more advanced algorithmic processing strategy can be used as facts become consolidated in a good mathematician (i.e., the association between the math fact and the answer is strengthened). In the reading domain, when words are unfamiliar to an individual with RD, the individual appears to resort to a basic visual/orthographic route and uses less advanced phonological processing strategies (Siegel, 2003). Consistently, when facts are unfamiliar to individuals with MD, a less efficient strategy is used. Geary (2004; 1994) referred to these less efficient strategies as 'backup' strategies (e.g., counting all). More advanced strategies

are associated with higher performance on math achievement tests (Geary, 2004; Siegler, 1988) and reading achievement tests.

Similar to children with RD who exhibit more errors and less fluency in word reading, Geary, Hamson and Hoard (2000) found that first grade children with MDs demonstrated significantly more errors (in retrieval and when counting-on) and more variability in their RT. Much like the progress from phonological decoding to consolidating the name of the whole word in orthographic store for fast retrieval in good readers, normal mathematicians showed progress from verbal counting to automatic retrieval, with faster retrieval times across Grades 1-2. RD and MD children did not show such advancement (Geary et al. 1991).

In the reading domain, a similar ‘additive’ system involving the visual/orthographic-phonological connection appears to be capitalized upon by empirically-supported reading remediation programs. For example, Lovett et al.’s (2000a) PHAST Reading program enhances sight word automaticity and phonological processing skills, and teaches metacognitive word identification strategies. As a student’s visual/orthographic store increases in automaticity, and they learn metacognitive strategies to employ phonological processing skills, the orthographic/visual-phonological connection can collaborate to facilitate accurate decoding of more unfamiliar words (e.g., Lovett et al., 2000a).

#### Functional Neurobiological Systems Underlying Cognitive Processes in Math

Functional neuro-imaging research shows that the fusiform gyrus is the perceptual processor for numbers and stores the visual forms (Rickard et al., 2000; Zago et al., 2001). This is also part of the automatic ventral system for reading. Similar to the storage and retrieval of automatic orthographic information, a left-hemisphere network associated with

storage and retrieval of automatic math facts has been identified (Dehaene & Cohen, 1997). The left ANG and SMG appear associated with automatic multiplication, but not with less automatic subtraction tasks (Lee, 2000). The prefrontal cortex appears associated with automaticity of math tasks (Menon et al., 2000b). Left parietal lesions are also implicated in the retrieval of arithmetical facts. (Mayer et al. (2003). The left ANG is active during more exact calculation for well-practiced math facts such as multiplication (DeHaene et al., 1999; Stanescu-Cosson et al., 2000). Delazer et al. (2003) found that ‘trained’ (i.e., automatic) multiplication problems were associated with greater activation in the left ANG, while less automatic or ‘untrained’ multiplication problems activated the left IPS and IFG. Taking the fMRI findings from the reading and math literature, there appears to be some potential overlap in areas associated with integrating word reading with phonological processes and with integrating math fact retrieval with algorithmic processes.

Geary (2004) has suggested that the procedural math disability subtype (e.g., characterized by procedural errors in calculations (such as errors in carrying or borrowing) appeared related to left-hemisphere systems. Geary (2004) reported that the relation between (e.g., underlying deficits in) a procedural math disability and a reading disability was unclear. In the inferior parietal lobe, the SMG, ANG, and IPS are activated during arithmetic processing (Zago & Tzourio-Mazoyer, 2002; Dehaene et al., 2003). A bilateral inferior parietal network is dedicated to the mental manipulation of numerical quantities (Dehaene & Cohen, 1993). More laboured number processing is associated with activation of fronto-temporal regions, and calculation procedures are associated with activation of parietal cortex (Dehaene et al., 1999, 2003). Based on this evidence, there appears to be a possible overlap between phonological processing and algorithmic processing regions.

With respect to the role of working memory, the superior frontal gyri (SFG) and MFG appear to be involved with executive processes associated with working memory and online mental calculations (Zago et al., 2001). Right frontal cortex damage is related to executive difficulties (e.g., monitoring and implementing multi-step problem-solving) in solving math calculations (Luria, 1980; Temple, 1991) and many other learning difficulties. Significant correlations between oral calculation and verbal working memory, and between written calculation and visuospatial working memory, have been reported (Mayer et al., 2003). The SMG appears related to working memory, and storing parts of the solutions (Zago & Tzourio-Mazoyer, 2002).

Lee and Kang (2002) found that a phonological dual task suppresses oral multiplication but not subtraction facts, and vice-versa for visuo-spatial dual tasks; this suggests that oral multiplication may be associated with the phonological loop (e.g., verbalization of multiplication facts), and subtraction with the visuo-spatial sketchpad (e.g., visualization of mental calculations). This makes sense given that multiplication facts provide more opportunity than subtraction for retrieval of automatic facts (e.g.,  $3 \times 3 = 6$ ). Left inferior parietal cortex has been claimed to be the site of the verbal short-term store, yet imaging studies report activation of a homologous right-hemisphere region in verbal working memory (Ravizza, Behrmann, & Fiez, 2005). Left ventral prefrontal cortex (PFC) appears to support preferentially verbal WM, and right dorsal PFC appears to support preferentially spatial WM. (Walter et. al., 2003.)

#### Cognitive Deficits in Comorbid RD+MD

Geary (1993) suggested that the retrieval of automatic math facts is dependent on a phonetic-semantic memory system and, therefore, should share the same resources as the

retrieval of words from long-term memory. This deficit in retrieval seen in single RD for words, and in MD for facts, could help explain this occurrence of comorbid RD+MD. As was suggested earlier, in the present study, it is proposed that an automatic visual- (orthographic or fact) system allows a word to be read in its entirety or the answer to a math fact to be reached, prior to phonological or algorithmic processing, or the semantic relation (i.e., meaning) to the word or answer being accessed. A deficit in automatic visual routes that directly accesses the name of an entire word or the answer to a math fact appears to characterize RD and MD groups; this suggests that RD+MD groups would have difficulty automatically retrieving both via a visual/orthographic and visual/fact route.

Evidence in support of this hypothesis includes reports of children with RD+MD performing poorly on tasks (i.e. RAN digits) that require the quick access of visual-verbal information (Denckla & Rudel 1976; Fawcett & Nicolson, 1994; Gathercole & Adams, 1994). Ackerman and Dykman (1995) suggested that a core weakness in children with RD or MD is processing speed, and that children with *both* arithmetic and reading disabilities are particularly impaired in this set of cognitive processes. Geary et al. (1999) assessed grade one children with MD, RD, and RD+MD, and results suggested that RD or RD+MD participants had slower speed of retrieval for familiar words relative to a normal group of grade one children. In addition, the RD+MD and MD groups committed more memory retrieval errors in automatic retrieval of arithmetic facts (Geary et al., 1991; Geary et al., 1999). Thus, weaker processing speed affected each group's ability to retrieve specific information differently.

Hitch and McAuley (1991) suggested that the children with MD had a domain-specific working memory deficit (e.g., with numbers), while the RD+MD group had a

general working memory impairment (e.g., with numbers and letters). Consistent with this hypothesis, Siegel and Ryan (1982) administered a counting span task and a sentence span task (adapted from Daneman & Carpenter, 1980) to a group of children with specific arithmetic disabilities, and found that they were impaired on counting span but not on sentence span. In contrast, the reading disabled group was found to be impaired on *both* tasks. Mental arithmetic (i.e., solving unfamiliar algorithms) has also been found to be particularly difficult for RD and RD+MD groups (Ackerman et al., 1986; Ackerman & Dykman, 1995).

Fletcher, Morris, and Lyon (2003) found that RD+MD children had more severe phonological awareness and working memory difficulties relative to single RD and MD groups. Leather and Henry (1994) found that, after controlling for verbal working memory, phonological awareness contributed to both reading and arithmetic achievement in a Grade 2 sample. However, phonological awareness accounted for a larger percentage of unique variance in word decoding than in arithmetic, suggesting that phonological awareness is more specific to reading than arithmetic achievement (Leather & Henry, 1994).

Ackerman and Dykman (1995) contrasted an RD and an RD+MD at two age levels, 8-12 years old and 12-17 years old. In both age ranges, the RD+MD group were significantly poorer on tasks of phonological skill, working memory, and naming speed. As with children with reading disabilities, Ackerman and Dykman suggested that RD+MD children also fall increasingly farther behind across development, and that this group displays a more pronounced 'Matthew Effect' ('the rich get richer and the poor get poorer') (Stanovich, 1986).

## Current Study

The evidence reviewed above suggests that RD children have potential cognitive deficits in their visual automatic/orthographic retrieval of RAN and sight words, phonological processing, and working memory span. It also implies that MD children have potential cognitive deficits in their visual automatic/math fact retrieval for math facts, algorithmic processing, and working memory span. Previous research suggests that a combination of cognitive processing deficits exists in RD+MD children, with potential weaknesses in their automatic visual/orthographic and automatic visual/math fact retrieval, phonological processing and algorithmic processing, and in their working memory span.

To validate the nature, type, and extent of deficits in single and comorbid disability groups, Part I of the current study assesses the similarities and differences in Grade 4 students' performance on tasks measuring specific cognitive processes associated with reading and/or math disabilities. These include: automatic visual/orthographic and visual/fact routes (e.g., RAN, words, and math facts), working memory span, phonological processing, algorithmic processing, and verbal/nonverbal reasoning in ND, RD, MD, and RD+MD subgroups.

In Part II of this study, Structural Equation Models (SEMs) for the entire sample are designed to explore the unique and shared variance of theoretically-derived factors representing the key cognitive processes suggested to underlie reading and math achievement. These processes include automatic retrieval (visual/orthographic and visual/fact), processing (phonological and algorithmic), and working memory span factors. Given that psychological assessments for reading and math learning disabilities often start with administration of an IQ test to obtain an estimate of expressive vocabulary, verbal and

nonverbal/reasoning, and visual-spatial analysis, a fourth IQ factor (i.e., verbal/nonverbal reasoning) is also designed into the SEM to explore its relation to the other three factors (e.g., automatic, processing, and working memory span).

To account for potentially different reading and math processes, a theoretically-derived four factor READ SEM and four factor MATH SEM were assessed through confirmatory factor analysis. Both models have two factors that are identified using identical measures. These are Working Memory Span (e.g., digit and letter span) and IQ (e.g., vocabulary, verbal and nonverbal reasoning, and visual-spatial analysis). The other two READ model factors represent the visual/orthographic route called Automatic (e.g., RAN/Words), and Phonological Processing. The other two MATH model factors represent the visual/fact route called Automatic (RAN/facts), and Algorithmic Processing. The READ and MATH models are designed to explore the validity and the unique variance of each factor along with the shared variance between each of the factors (i.e., intercorrelations).

Based on cognitive and functional neurobiological research on the cognitive processing deficits associated with reading and/or math disabilities, a systems analysis was run using these READ and MATH SEM models. Within each of the READ and MATH systems (i.e., models), it was proposed that the automaticity factor represents common cognitive (and functional neurobiological) processes underlying reading and math achievement that requires the ability to rapidly identify the sound or name associated with visual information (e.g., familiar letters, digits, words, and math facts). When these words and facts are unfamiliar, or not automatically identifiable as a whole, more advanced ‘strategy-based processes’ must ‘kick in.’ These advanced processes are represented by the

phonological processing (awareness and decoding) factor, the algorithmic (calculation and procedure) processing factor, and the verbal/nonverbal reasoning factor.

Significant intercorrelations between these factors would represent how these four cognitive processes work in partnership. Theoretically, it is proposed that efficient readers and mathematicians increase word reading and math calculation efficiency by first retrieving the part of the word or fact that has already been automatically identified. Then they must employ working memory span, utilizing verbal rehearsal and/or visualization to keep the familiar and currently unfamiliar parts, ‘online’ in a working order. The more automatically information is identified (e.g., immediately reading a whole word form, or identifying the solution to a math fact), the more capacity the working memory system has for higher processing loads. The capacity of verbal and visual working memory span places limits on the amount the higher order processes can simultaneously keep online to ‘work on.’ Good readers and good mathematicians’ strong phonological or algorithmic processing and IQ reasoning ability are proposed to enhance this system’s accuracy.

Should the READ and MATH SEM models be validated, showing best fit and significant unique (i.e., significant latent variables) and significant shared variance (i.e., intercorrelations), findings would support this proposed system. That is, the findings would be compatible with the speculation that the automatic, processing, working memory, and verbal/nonverbal fluid reasoning within the proposed READ and MATH systems work uniquely and in collaboration to try to increase the storage capacity, accuracy, fluency, and overall efficiency of the system.

In Part III of the study, the theoretically-derived composites from the READ and MATH factors were entered into separate stepwise regression equations to predict reading

achievement (e.g., word reading and decoding), and math achievement (e.g., fluency, calculation and problem-solving). This allowed for further exploration into what specific cognitive processes might predict age-appropriate or below-age performance on reading and math achievement tests for each of the ND, RD, MD, and RD+MD groups. This could help to elucidate the strong or weak cognitive processes that these groups rely on when reading words, decoding, solving simple math facts, or solving math calculations and math problems.

Finally, by entering in READ composites to predict math achievement tests and MATH composites to predict reading achievement tests, potential overlap in automatic-visual routes for words and math facts (e.g., good automatic math fact retrieval predicts good automatic word reading or visa versa) could be explored. This statistical exploration was motivated by amalgamating findings from previous research suggesting overlap in strong automatic visual/orthographic and visual/fact routes in good readers and mathematicians, and overlap in automatic visual/orthographic and visual/fact route deficits in RD+MD samples. It was also motivated by the separate fMRI research showing potentially similar functional neurobiological pathways in reading and math (for review, see Fletcher, Lyon, Fuchs, and Barnes (2007)). This method also allows for further exploration into possible overlap in phonological and algorithmic processing, and the unique or collaborative contribution of working memory span and verbal/nonverbal reasoning to good or poor reading and/or math achievement.

## METHOD

### Participants

A total of 240 Grade 4 students from schools in the Waterloo Region District School Board (WRDSB), Waterloo Catholic District School Board (WCDSB), and the Toronto

Catholic District School Board (TCDSB), were initially screened for: 1) IQ using the Wechsler Abbreviated Scale of Intelligence (WASI) VIQ (Vocabulary and Similarities subtests), and PIQ (Matrix Reasoning and Block Design); and 2) Reading and Arithmetic skill level using the Woodcock-Johnson Tests of Achievement, Third Edition, Form B (WJ-III, Achievement, Form B (Woodcock & Johnson, 1989)) subtests including: Letter-Word Identification (LWID), Word Attack (WA), and Calculation (Calc.).

Pre-determined cut-off criteria were used to select the current sample. First, students were selected if their WASI VIQ and/or PIQ fell within the average range (25<sup>th</sup>-74<sup>th</sup> percentile). From these selected students, four groups were created based on their WJ-III, Achievement, Form B, scores on LWID, WA, and Calc. These groups were: 1) ND (Good Read/Good Math) with standard scores  $\geq 85$  on LWID, WA, and Calc.; 2) RD (Poor Read/Good Math) with standard scores  $\leq 85$  on WA and/or LWID, and standard scores of  $\geq 85$  on Calculation; 3) MD (Good Read/Poor Math) with standard scores of  $\geq 85$  on WA and/or LWID, and standard scores of  $\leq 85$  on Calculation; and 4) RD+MD (Poor Read/Poor Math) with standard scores  $\leq 85$  on WA and/or LWID, and standard scores of  $\leq 85$  on Calculation.

Ethics approval for this study was given by the University of Waterloo Ethics Department and by The Hospital for Sick Children Research Ethics Board (REB). Students in the four groups underwent two more testing sessions for dependent measures; with at least a two week interval between sessions. Parental consent was obtained for all sessions, and all children participated on a voluntary basis. All children were fluent English speakers and had no reported history of serious medical conditions or head injury.

## *Session 1: Screening Tests and Measures*

### *Intelligence (IQ)*

*Wechsler Abbreviated Scale of Intelligence (WASI)*. The four-subtest form results in a Full Scale Intelligence Quotient (FSIQ) comprised of two indices: 1) Verbal IQ (VIQ), and 2) Performance IQ (PIQ) scores. The VIQ score is comprised of two subtests, including: 1) Vocabulary, requiring expressive vocabulary to provide the definitions of words, and 2) Similarities, requiring verbal reasoning to find the similarity between two items or concepts. The PIQ is also estimated by two subtests: 1) Matrix Reasoning, for measuring nonverbal reasoning abilities to identify patterns in series of two-dimensional matrices, and 2) Block Design, for measuring visual-spatial and fine-motor manipulation and integration (mental and manual rotation) of three-dimensional blocks to recreate two-dimensional designs. Raw scores for each subtest were transformed into T scores based on age. FSIQ, VIQ, and PIQ were calculated using these T scores. Next, T scores were converted to standard scores, which were used in the current analyses.

### *Reading and Math Skill Assessment, WJ-III, Achievement Tests, Form B*

*Letter-word identification (LWID)*. This is a standardized measure of isolated letter and real word (e.g., investigate) reading accuracy. Words increase in difficulty across the test, and testing is discontinued after six consecutive errors. Raw accuracy scores were transformed into standard scores based on age. Standard scores were used to assign children to one of the four groups. Raw and standard scores were both used in the current analyses.

*Word attack (WA)*. This is a standardized measure of nonword decoding accuracy. Children are asked to read nonsense words, such as ‘nat’ or ‘snirk’, containing high frequency English language phonemes, and their response is assessed against a correct

pronunciation provided by WJ-III. Items increase in difficulty across the test, and testing is discontinued after six consecutive errors. Raw accuracy scores are then transformed into standard scores based on age. Standard scores were used to assign children to one of the four groups. Raw and standard scores were used in the current analyses.

*Calculation (Calc.).* This is a standardized measure of the ability to use a pencil and paper to accurately solve single and multidigit algorithms requiring addition, subtraction, multiplication, and division operations (e.g.,  $1 + 2 =$ ). Items increase in difficulty across the test, and testing is discontinued after six consecutive errors. Raw accuracy scores were then transformed into standard scores based on age. Standard scores were used to assign children to one of the four groups. Raw and standard scores were used in the current analyses.

*Applied Problems (App. Prob.).* This task was administered during the screening session and used for later analyses. It was not used as a screening tool. This is a standardized measure of the ability to solve aurally administered ‘practical’ math problems (e.g., ‘Four people have \$3.00 each. How much do they have in total?’). Children were offered the use of a pencil and paper, should they wish to use it. Items increase in difficulty across the test, and testing was discontinued after six consecutive errors. Raw accuracy scores were then transformed into standard scores based on age. Raw and standard scores were used in the current analyses.

#### *Session Two and Three: Tests Administered to Each of the Four Groups*

##### *Executive Function/Reasoning Tasks*

*Planning (WJ- III Cognitive Battery, Form B) (Woodcock, McGrew, & Mather, 2001).* A series of mazes, increasing in difficulty, were presented one at a time to each child. Each maze has a start point and the child is asked to plan towards the maze’s exit. It required

planning in advance toward a series of ‘exits’ or goals. The task is discontinued after three consecutive errors. Raw and standard scores were used in the current analyses.

*Concept Formation (WJ- III Cognitive Battery, Form B) (Woodcock, McGrew, & Mather, 2001).* Each child was asked to figure out missing pieces in a selection of puzzles. Conceptual inferences and reasoning are required to select the correct answer. This test is discontinued after six errors. The task finishes after three consecutive errors. Raw and standard scores were used in the current analyses.

#### *Measures of Automatic Retrieval*

*Rapid Automated Naming Tests for Letters (RAN:L).* The RAN:L requires speeded naming of a continuous array of letters. To ensure that children were familiar with the letters, they are first asked to identify the five letters on a sheet of paper. On this task, the child is presented with a display of 50 letters (the five letters in mixed order) and asked to say each letter out loud as quickly as possible, reading from left-to-right, without making mistakes. The letter matrix is made up of five rows with ten letters presented on each row. Time to name the items on each trial was recorded in milliseconds, using a stopwatch, along with any errors that the child made (e.g., skipped digits, substitutions, reversals). The total time, total correct, and number of letters read correctly per second were used in the current analyses.

The format for the test is adapted from that used by Denckla & Rudel (1974).

*Rapid Automated Naming tests for Digits (RAN:D).* The RAN:D is identical in administration to the RAN:L except that five digits are used instead of five letters. The total time, total correct, and number of digits read correctly per second were used in the current analyses.

### *Word Reading*

*Exception word list (Lovett, 1987).* This is a list of 108 exception words of (high, medium, and low frequency) containing exceptional or irregular spelling patterns. To a good reader, these patterns require use of a visual/orthographic-naming route to read as they are difficult, in part, to phonetically decode (e.g., island). The list was presented in the same random order to each of the children. The child was asked to read as many of the words from the list, trying their best to read correctly and as quickly as possible. If they had tried their best and did not know the answer, they were instructed to say ‘skip.’ It is an experimental (i.e., unstandardized) measure and total correct, total time, and total words read correctly per second were used in the current analyses.

*Benchmark key word list (Gaskins et. al., 1986; 1988).* This is a list of 120 regular words containing the highest frequency spelling patterns in the English language. To a good reader, these words become more easy to read through a visual/orthographic-naming route as they require minimal, if any, phonological decoding. The list was presented in the same random order to each of the children. The child is asked to read as many of the words from the list, trying their best to read correctly and as quickly as possible. If they had tried their best and did not know the answer, they were instructed to say ‘skip.’ This is an unstandardized measure and total correct, total time, and total words read correctly per second were used in the current analyses.

### *Automatic Math Fact Retrieval*

*Math fluency (M. Fl).* This is a standardized measure from the WJ-III, Achievement, Form B. Each child is shown a series of basic single-digit addition, subtraction, and multiplication problems and asked to use a pencil and paper to quickly and accurately

complete as many as possible until the examiner says ‘stop’ (after three minutes). Raw accuracy scores were transformed into standard scores based on age. Standard scores, total correct, total time (180 seconds), and number of correct facts per second were used in the current analyses.

*Math facts (Evans, 2008).* Similar to the Benchmark and Exception word lists, on the following math fact calculations, the child is asked to say their answer to each math fact out loud, as correctly and as quickly as possible, trying their very best. They were also told that they could say, ‘skip’ if they have given their best try, and were really stumped on a question. Compared to Math Fluency, this is an oral task and it is an experimental (i.e., unstandardized measure). Total time, and total correct were recorded along with ‘Automatic’ correct answers given in less than or equal to one second, and ‘processed/working memory’ correct answers that took longer than one second. Total time, total correct, total correct per second, ‘automatic’ and ‘processed/working memory’ were used in these analyses. For each of the following addition, subtraction, multiplication, and division calculations two sets of scores are obtained for an ‘easy’ and a ‘difficult’ set of number facts.

- i. *Addition facts (Easy and Difficult):* Two sets of horizontal number calculations (easy and difficult) are presented separately on a sheet of paper for the child to complete orally. The easy set includes 35 addition calculations whose sum was less than 10 (e.g.,  $4+5$ ) and the difficult set includes 30 addition calculations whose was greater than ten and less than 21 (e.g.,  $9+7$ ).
- ii. *Subtraction facts (Easy and Difficult):* Two sets of horizontal number calculations (easy and difficult) are presented on two separate sheets of paper for the child to complete orally. The easy set includes 35 subtraction calculations whose answer was

- less than 10 (e.g., 10-1) and the difficult set includes 30 subtraction calculations whose answer was greater than ten and less than 19 (e.g., 19-2).
- iii. *Multiplication facts (Easy and Difficult)*: Two sets of horizontal number calculations (easy and difficult) are presented on two separate sheets of paper for the child to complete orally. The easy set included 22 multiplication calculations in which at least one factor was less than or equal to 5 (e.g., 3x7) and the difficult set included 24 multiplication calculations in which both factors were greater than six and less than or equal to 11 (e.g., 8x9).
- iv. *Division facts (Easy and Difficult)*: Two sets of horizontal division calculations (easy and difficult) are presented on two separate sheets of paper for the child to complete orally. The easy set included 22 division calculations in which the divisor was less than or equal to 5 (e.g., 20 ÷4), and the difficult set included 24 division in which the divisor fell between 6 and 11 (e.g., 40÷8).

#### *Working Memory Span*

*Digits Forwards (Wechsler Intelligence Scale for Children- Third Edition (WISC-III))*. Children are read a series (from one to nine) of single digits (e.g., 2, 5) one at a time (1 second each). The child is then asked to recall the series of digits in the exact order that he/she heard them. There are eight levels; level one contains two digits and one more digit is added for each level, so that the eighth level has nine digits. Each level has two trials. This task is discontinued if the child answers incorrectly to both trials at one level. Standard and raw scores were used in the current analyses.

*Digits Backwards (WISC-III)*. Children are read a series of numbers and are asked to recall them in the reverse order (e.g., given '2, 5', the correct answer was '5, 2'). There are

seven levels; level one contains two digits and one more digit is added for each level so that the seventh level has eight digits. Each level has two trials. This task is discontinued if the child answers incorrectly to both trials at one level. Standard and raw scores are used in the current analyses.

*Letters Forwards and Backwards.* Digits Span from the WISC-III uses digits from 1-9. To create a 'letter' version, each digit was assigned a consonant starting at the beginning of the alphabet (i.e., 1-b, 2-c, 3-d, 4-f, 5-g, 6-h, 7-j, 8-k, 9-l). Vowels were not used. Each of the digit strings for digits forward and backward were replaced by their corresponding letter. The tasks were administered in an identical fashion to Digit Span from the WISC-III as outlined above.

*Letters Forwards.* Each child is read a series of single letters (e.g., d, c) one at a time (1 second each). The child is then asked to recall the series of letters in the exact order that he/she heard them. There are eight levels; level one contains two letters and one more letter is added for each level so that the eighth level has nine letters. Each level has two trials. This task is discontinued if the child answers incorrectly to both trials at one level. Standard and raw scores are used in these analyses.

*Letters Backward.* Children are read a series of letters and are asked to recall them in the reverse order (e.g., given 'd, c', the correct answer was 'c, d'). There are seven levels; level one contains two letters and one more letter is added for each level so that the seventh level has eight letters. Each level has two trials. This task is discontinued if the child answers incorrectly to both trials at one level. Standard and raw scores are used in these analyses.

### *Phonological Processing*

*Elision subtest.* A standardized subtest from the Comprehensive Test of Phonological Awareness (CTOPP) (Wagner, Torgeson, & Rashotte, 1999) that measures awareness of the sound structure of English words by assessing the ease by which an individual can say a word, then segment, delete, and re-blend sounds to create a new word. For example, the child is asked to say 'bold' and after repeating 'bold,' is asked, 'Now say bold without saying /b/.' The correct response is 'old.' This task is highly correlated to phonological 'working' memory tasks as the child must hold the sound parts in working memory in order to carry it out. Raw scores were converted to standard scores using age. Raw and standard scores were used in the current analyses.

*Nonword Repetition subtest (CTOPP)* (Wagner, Torgeson, & Rashotte, 1999). A 20-item subtest that measures phonological 'working' memory or a child's ability to code phonemes from nonwords (containing high frequency phonemes) and temporarily store them in phonological 'working' memory in order to repeat them correctly. The child listens to a series of audiocassette-recorded separate sounds and is asked to 'put them together to make a nonword.' For example, the child was asked, 'What word do these sounds make: nim-by?' The correct answer is the nonword 'nimby.' Raw scores were converted to standard scores using age. Raw and standard scores were used in the current analyses.

### *Algorithmic Processing*

*Canadian KeyMath-Revised-Addition Subtest.* Each child is asked to solve paper and pencil multi-digit addition algorithms. The task is discontinued after three consecutive errors. Raw accuracy scores are then transformed into standard scores based on age. Raw and standard scores were used in the current analyses.

*Canadian KeyMath-Revised: Subtraction Subtest.* Each child is asked to solve paper and pencil multi-digit subtraction problems. The task finishes after three consecutive errors. Standard scores were both used to assign children in one of the four groups. Raw and standard scores were used in the current analyses.

*Canadian KeyMath-Revised: Multiplication Subtest.* Each child is asked to solve paper and pencil multi-digit multiplication problems. The task finishes after three consecutive errors. Standard scores were used to assign children in one of the four groups. Raw and standard scores were used in the current analyses.

*Canadian KeyMath-Revised: Division Subtest.* Each child is asked to solve paper and pencil multi-digit division problems. The task is discontinued after three consecutive errors. Raw and standard scores were used in the current analyses.

PART I

Procedure

*Comparing Group Means*

First, an ANOVA was run to assess for significant differences between and within groups on each variable. Next, three a priori orthogonal contrasts were examined: 1) No Disability (ND) compared to all three disability groups (reading (RD), math (MD), and reading/math (RD+MD)); 2) RD+MD group compared to the two single Disability groups (RD and MD), and 3) RD group compared to the MD group. These contrasts are outlined on Table 1. To further specify significant differences between individual groups, Bonferroni post-hoc analyses were run and evaluated at a significance level of .02, to reduce Type 1 Error. Standard scores were used when available. If unavailable, raw scores were used.

Table 1.

*Description of Planned Comparisons*

Planned Comparison	<u>ND (N=72)</u>	<u>RD (N=36)</u>	<u>MD (N=65)</u>	<u>RD+MD (N=50)</u>
1. ND vs. RD, MD & RD+MD	3	-1	-1	-1
2. RD & MD vs. RD+MD	0	1	1	-2
3. RD vs. MD	0	1	-1	0

## Results

### *Descriptive Statistics*

For each of the four groups (ND, RD, MD, and RD+MD) age, sex, and handedness are summarized in Table 2. The total sample included 223 children.

Table 2.

#### *Description of Age, Sex, and Handedness for the Four Groups*

Descriptive	<u>ND (N=72)</u>		<u>RD (N=36)</u>		<u>MD (N=65)</u>		<u>RD+MD (N=50)</u>	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Age	9.72	.71	10.06	1.03	10.21	1.21	10.98	1.59
Male	29		22		31		23	
Female	43		14		32		26	
Right Handed	62		30		57		43	
Left Handed	10		6		8		7	

Age in years and months at first test session.

WASI IQ

Table 3.

*Mean Performance and Standard Deviations for the Four Groups on the WASI Verbal IQ (Vocabulary and Similarities), Performance IQ (Matrix Reasoning and Block Design, and 'Executive' Tests – Concept Formation and Planning*

	ND (N=72)		RD (N=36)		MD (N=65)		RD+MD (N=60)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Verbal IQ	106.08	11.93	95.42	10.44	100.18	10.72	88.74	9.42
Vocabulary	105.67	13.59	94.38	9.54	97.42	11.43	86.20	10.40
Similarities	105.84	12.28	96.38	13.82	103.00	11.97	90.85	12.79
Performance IQ	100.17	9.56	98.19	9.84	98.08	12.14	89.94	12.16
Matrix Reasoning	101.38	9.95	98.71	11.84	97.44	13.08	86.71	15.31
Block Design	99.38	13.29	98.33	13.81	99.12	14.91	93.82	13.08
Concept Formation	101.80	10.13	95.40	9.03	96.05	9.09	89.02	9.57
Planning	109.42	6.57	108.89	8.95	107.12	9.52	106.00	9.21

## Verbal IQ

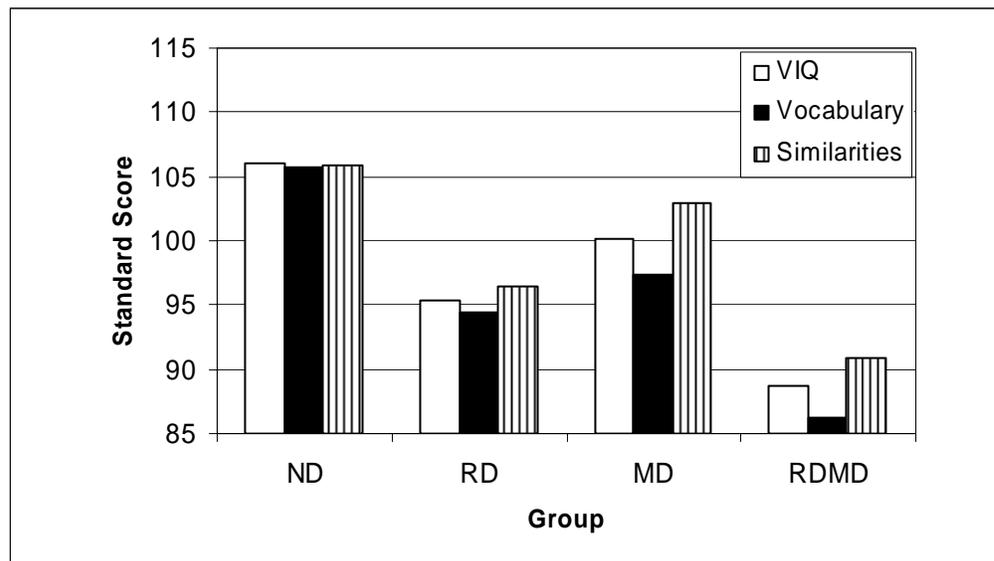


Figure 1. Mean group standard scores for WASI VIQ, Vocabulary, and Similarities.

Each group's VIQ scores are seen in Table 3 and in Figure 1. ANOVA comparisons showed significant differences between all four groups' VIQ scores ( $F(3,222) = 26.817$ ,  $p < .01$ ). Assuming equal variance, planned comparisons showed the ND group to have significantly higher VIQ than the three disability groups ( $t(219) = 7.23$ ,  $p < .01$ ). Planned comparisons did not show significant differences between the RD and MD group ( $t(219) = -2.12$ ). The RD and MD group had significantly higher VIQ than the RD+MD group ( $t(219) = 4.77$ ,  $p < .01$ ). Bonferroni tests specified that the MD group had significantly higher VIQ than the RD+MD group ( $p < .01$ ).

*Vocabulary.* Each group's mean standard scores are seen in Table 3 and Figure 1. ANOVA comparison showed significant differences between all four groups Vocabulary standard scores ( $F(3,222) = 28.00$ ,  $p < .01$ ). Assuming equal variance, planned comparisons showed the ND group had a significantly higher Vocabulary score than the other three groups ( $t(219) = 7.69$ ,  $p < .01$ ). The two single disability groups did not significantly differ from

each other ( $t(219) = -1.25$ ). Both had a significantly higher Vocabulary than the RD+MD group ( $t(219) = 4.72, p < .01$ ). Bonferroni tests confirmed this (MD vs. RD+MD group  $p < .01$ , and RD vs. RD+MD group  $p = .01$ ).

*Similarities.* Each group's mean standard scores are seen in Table 3 and Figure 1. ANOVA comparison showed significant differences between all four groups' Similarities standard scores ( $F(3,222) = 16.28, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group had significantly higher Similarities than the other three groups ( $t(219) = 5.02, p < .01$ ). Bonferroni tests specified that the ND group had significantly higher Similarities scores than the RD ( $p = .002$ ) and the RD+MD groups ( $p < .01$ ), with no significant difference between the ND and MD groups ( $p = 1.0$ ). The MD group had a significantly higher score than the RD group ( $t(219) = -2.54, p < .01$ ). Bonferroni tests showed that the MD group had a significantly higher Similarities score than the RD+MD group ( $p < .01$ ) and the RD and RD+MD groups were not significantly different.

WASI Performance IQ (Matrix Reasoning and Block Design Subtests):

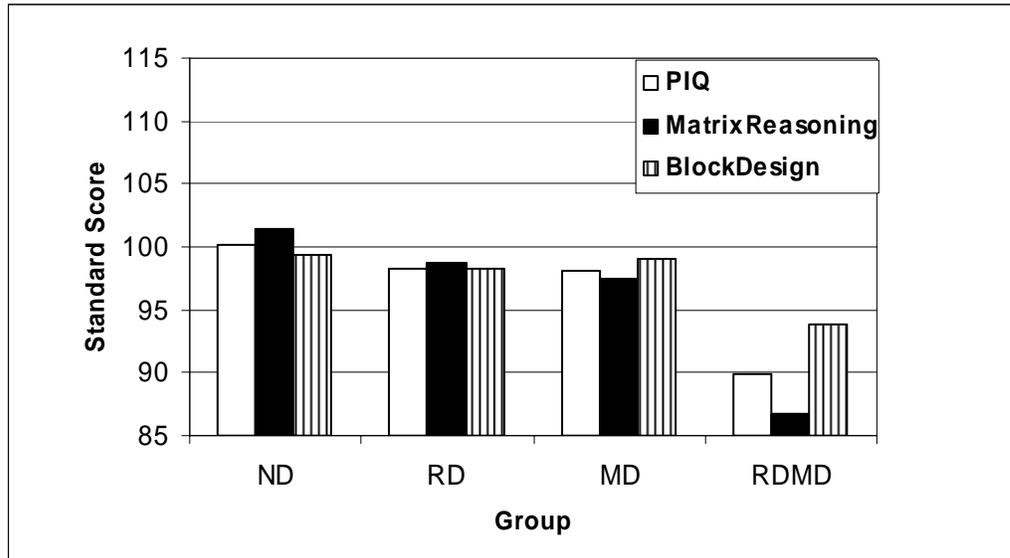


Figure 2. Mean standard scores on WASI PIQ, Matrix Reasoning, and Block Design.

*PIQ.* Each group's mean standard scores are seen in Table 3 and Figure 2. ANOVA comparison showed significant differences between all four groups PIQ scores ( $F(3,222) = 9.18, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group to have significantly higher PIQ than the three disability groups ( $t(219) = 2.99, p < .003$ ). Bonferroni tests specified that the main significant difference was between the ND group and the RD+MD group ( $p < .01$ ). The RD group did not significantly differ from the MD group, and both single disability groups had significantly higher PIQ than the RD+MD group ( $t(219) = 0.51, p < .01$ ).

*Matrix Reasoning.* Each group's mean standard score is seen in Table 3 and Figure 2. ANOVA comparison showed significant differences between all four groups' ( $F(3,222) = 14.29, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group had a significantly higher Matrix Reasoning score than the other three groups ( $t(219) = 3.91, p < .01$ ). Bonferroni tests specified that the main significant difference existed between the ND

and RD+MD group ( $p < .01$ ). While the two single disability groups did not significantly differ from each other, both had a significantly higher Matrix Reasoning score than the RD+MD group ( $t(219) = 5.17, p < .01$ ).

*Block Design.* Each group's mean standard score is seen in Table 3 and Figure 2. ANOVA comparison showed no significant differences between all four groups.

*Executive Function Tasks: Concept Formation and Planning*

*Subtests*

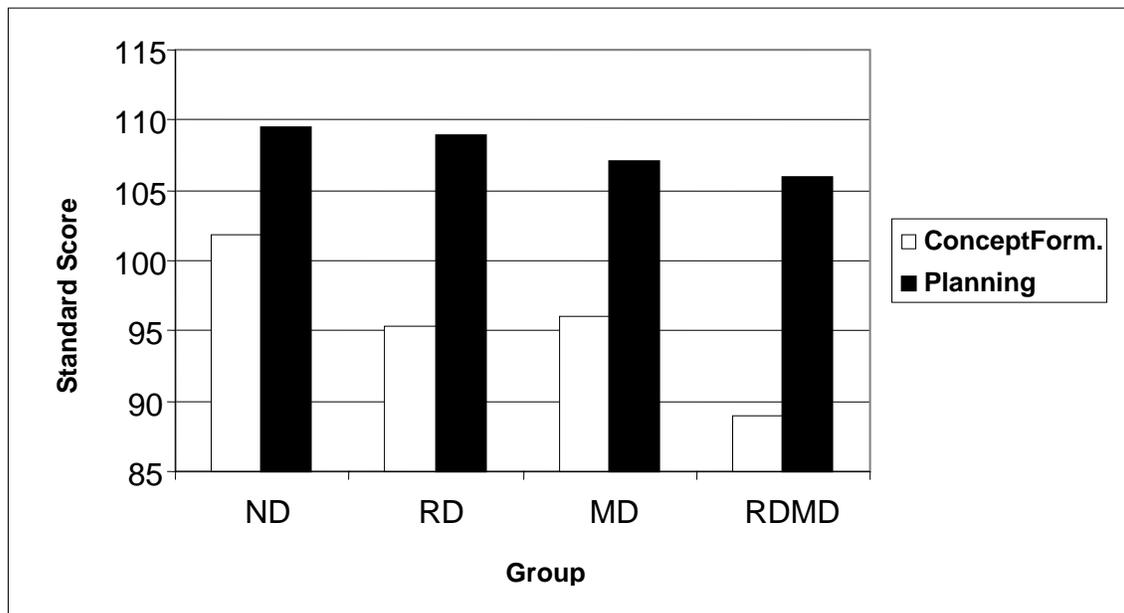


Figure 3. Mean standard scores on WJ-III cognitive Concept Formation (Concept Form.) and Planning subtests.

*Concept Formation.* Each group's mean standard score is seen in Table 3 and Figure 3. Initial ANOVA comparison showed significant differences between groups' standard scores ( $F(3,211) = 17.19, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group had significantly higher standard scores than all three disability groups ( $t(211) = 5.93, p < .01$ ). Bonferroni tests confirmed this (RD group  $p = .006$ ; MD group  $p = .004$ ,

and RD+MD group  $p < .01$ ). The RD and MD groups did not have significantly different scores and they both had significantly higher scores than the RD+MD group ( $t(211) = 3.93, p < .01$ ).

*Planning.* Each group's mean standard score is seen in Table 3 and Figure 3.

ANOVA comparison did not show significant differences between groups' standard scores.

*Comparing Nonverbal Reasoning (Matrix Reasoning and Concept Formation) versus Visual Spatial Ability (Block Design and Planning)*

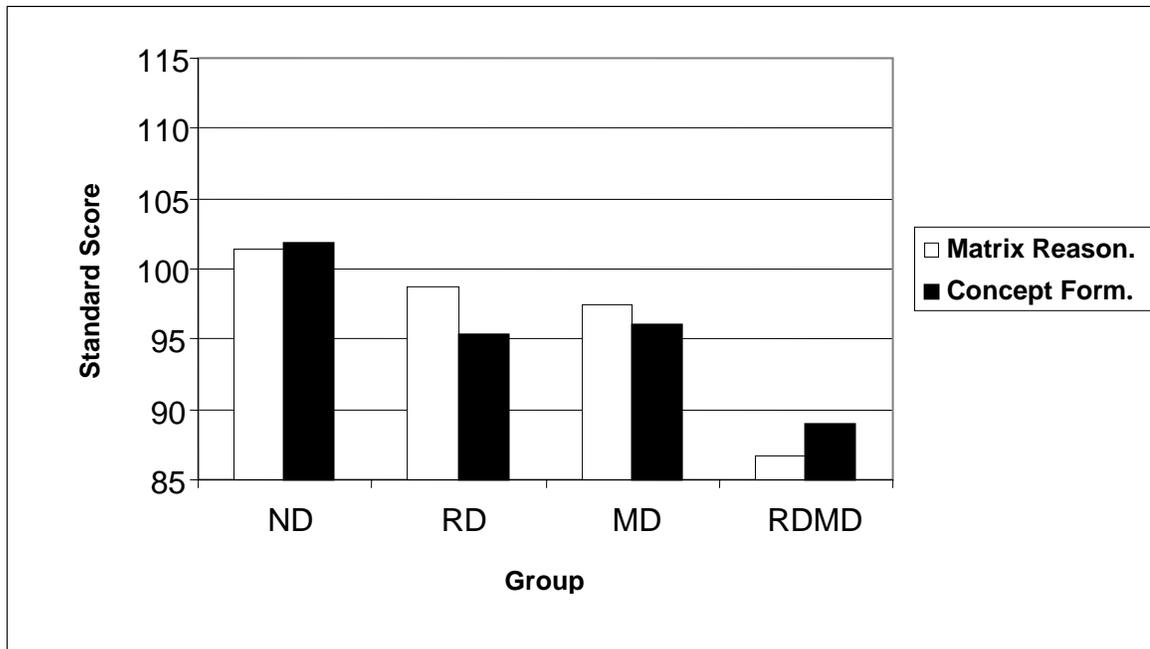


Figure 4. Mean standard scores on WASI Matrix Reasoning (Matrix Reason.) and WJ-III Concept Formation (ConceptForm.).

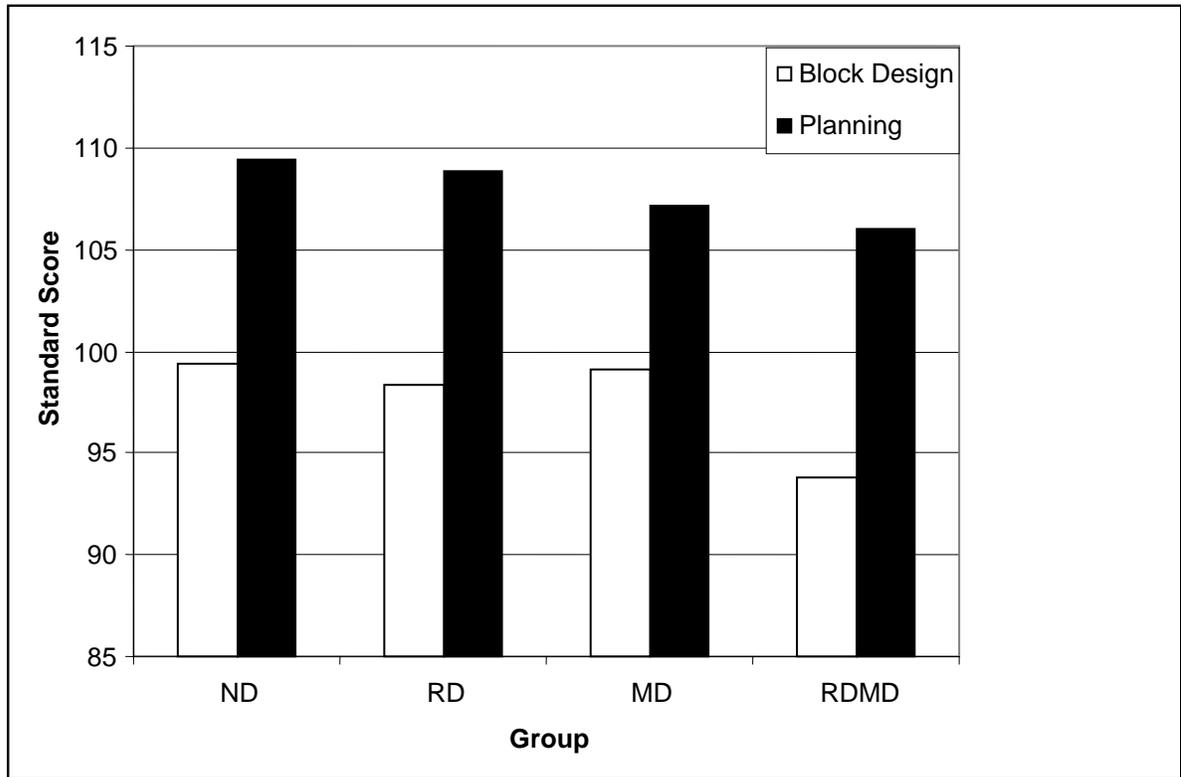


Figure 5. Mean standard scores on WASI Block Design and WJ-III Planning.

As seen in Figure 4 the RD+MD group showed relatively weaker conceptual reasoning ability on Matrix Reasoning and Concept Formation than the ND, RD, and MD groups. All groups demonstrated solidly Average visual-spatial and graphomotor ability on Block Design and Planning (as seen in Figure 5).

*Reading and Math Skills*

Table 4.

*Mean Performance and Standard Deviations for the Four Groups on Letter Word*

*Identification (LWID), Word Attack (WA), Calculation, Applied Problems, and Math Fluency*

WJ-III subtest	ND (N=72)		RD (N=36)		MD (N=65)		RD+MD(N=60)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
LWID r.s.	51.96	5.11	42.53	5.1	52.83	6.36	42.12	6.55
LWID st.s.	102.04	7.15	86.67	6.50	100.98	8.42	81.60	8.06
WA r.s.	21.56	4.3	11.75	4.48	21.74	4.73	11.98	5.55
WA st.s.	102.24	6.48	87.97	5.17	101.63	7.65	84.84	9.57
Read Composite st.s.	102.25	6.72	86.83	4.90	101.34	8.22	82.72	7.98
Calculation r.s.	15.99	2.49	16.22	2.54	11.86	2.90	13.37	3.20
Calculation st.s.	97.04	5.13	95.11	4.55	80.86	8.12	80.85	8.09
Applied Problems r.s.	35.46	3.46	34.28	3.10	33.00	3.87	31.9	4.42
Applied Problems st.s.	104.62	6.89	98.97	6.61	95.11	9.68	88.08	7.84
Math Fluency r.s.	54.96	16.75	46.99	13.30	46.56	14.91	47.84	16.73
Math Fluency st.s.	94.92	11.98	85.25	8.95	84.07	11.59	79.84	8.85
Calculation Comp. st.s.	96.69	6.51	92.22	4.39	80.87	8.02	78.56	10.41
Broad Math Comp. st.s.	100.48	5.72	95.53	4.20	87.95	7.02	83.28	7.57

r.s. = raw score; st.s. = standard score

*Standardized Reading Measures: WJ-III Achievement, Letter-Word Identification (LWID) and Word Attack (WA)*

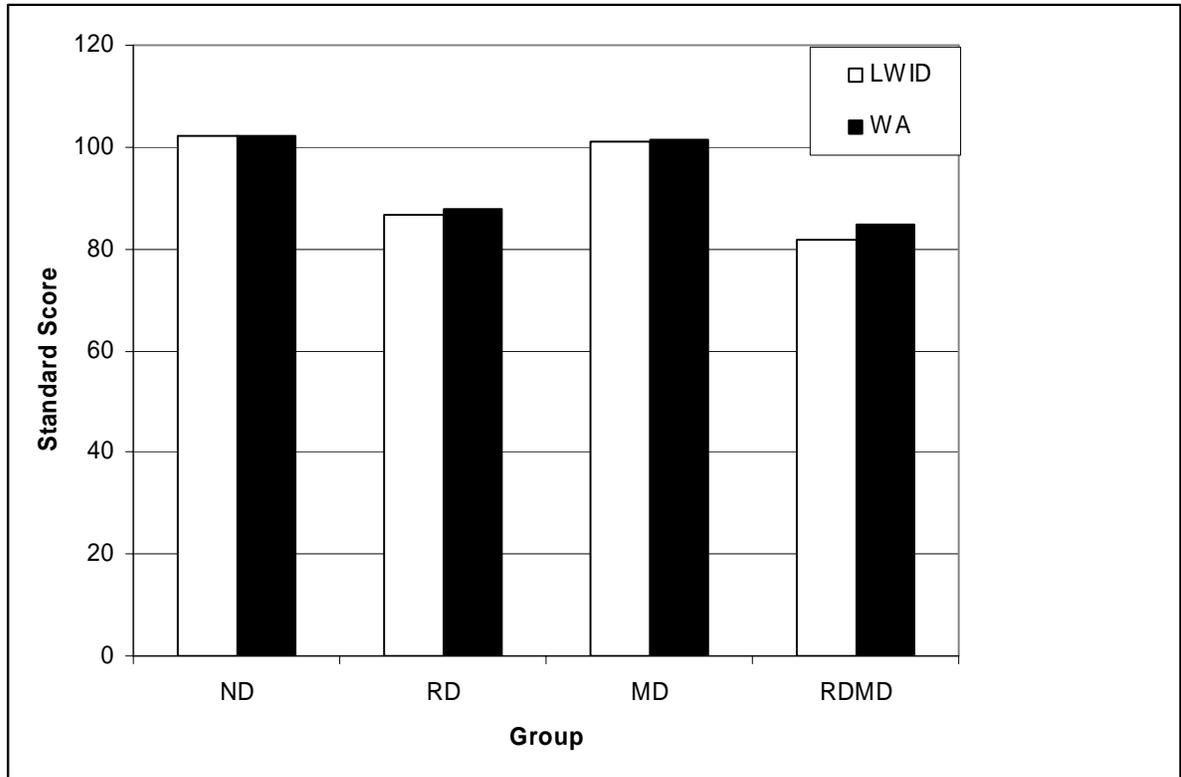


Figure 6. Mean standard scores on WJ-III Letter-Word Identification (LWID) and Word Attack (WA)

*Letter Word Identification.* Each group's mean standard score can be seen in Table 4 and Figure 6. ANOVA comparisons showed significant differences between groups ( $F(3,222) = 98.79, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group to have significantly higher LWID than the three disability groups ( $t(219) = 11.11, p < .01$ ). Bonferroni tests confirmed the ND group to have significantly higher LWID than the RD and RD+MD group (both at  $p=.000$ ) with no significant difference between the MD and ND group. The MD group had significantly higher LWID than the RD group ( $t(219) = -9.007, p < .000$ ), and Bonferroni tests showed that MD group had higher LWID than the

RD+MD group ( $p < .01$ ). Bonferroni tests showed that the RD group had higher LWID than the RD+MD group ( $p = .016$ ).

*Word Attack.* Each group's mean standard score can be seen in Table 4 and Figure 6. Initial ANOVA comparisons showed significant differences between groups ( $F(3,222) = 80.48, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group to have significantly higher WA than the three disability groups ( $t(219) = 9.98, p < .01$ ). Bonferroni tests confirmed that the ND group had significantly higher WA than the RD and RD+MD group ( $p < .01$ ) with no significant difference between the MD and ND group. The MD group had significantly higher WA than the RD group ( $t(219) = -8.82, p < .000$ ). Bonferroni tests showed no significant difference between the RD and RD+MD group ( $p = .334$ ).

*Standardized Math Measures: Calculation( Calc.), Applied Problems (App. Prob.) and Math Fluency (Mfl.)*

ANOVA comparisons showed significant differences between groups' standard scores on App. Prob. ( $F(3,222) = 44.70, p < .01$ ), Calc. ( $F(3,221) = 97.99, p < .01$ ), and MFl. ( $F(3,222) = 22.19, p < .01$ ).

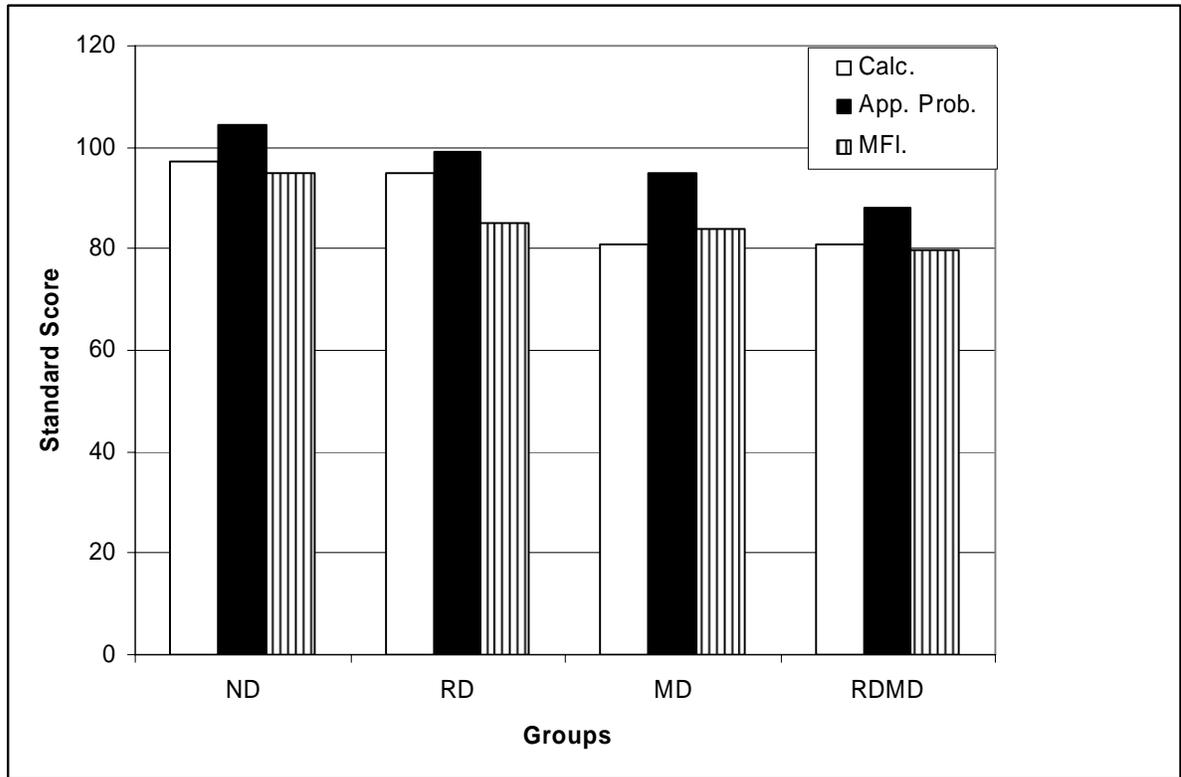


Figure 7. Mean standard scores on WJ-III Calculation (Calc.), Applied Problems (App. Prob.), and Math Fluency (MFI.)

*Applied Problems.* Each group's mean standard score can be seen in Table 4 and Figure 7. Assuming equal variance, planned comparisons showed the ND group to have significantly higher scores on App. Prob. ( $t(219) = 9.17, p < .01$ ), than the three disability groups. Bonferroni tests confirmed that the ND group had higher scores than the RD ( $p = .004$ ), MD and RD+MD group ( $p < .01$ ). Both single disability groups had significantly higher App. Prob. ( $t(219) = 6.40, p < .01$ ) than the RD+MD group, as confirmed by Bonferroni tests ( $p < .01$ ).

*Calculation.* Each group's mean standard score can be seen in Table 4 and Figure 7. Assuming equal variance, planned comparisons showed the ND group to have significantly higher scores on Calc. ( $t(218) = 11.66, p < .01$ ) than the three disability groups. Bonferroni

tests specified that the ND group had significantly higher Calculation than the MD and RD+MD group ( $p=.000$ ) but not the RD group. The RD group had significantly higher Calc. ( $t(218) = 10.12, p < .01$ ) than the MD group. Bonferroni tests showed no significant difference between the MD and RD+MD group ( $p < .01$ ).

*Math Fact Fluency.* Each group's mean standard score can be seen in Table 4 and Figure 7. Assuming equal variance, planned comparisons showed the ND group to have significantly higher scores on MFl. ( $t(219) = 7.61, p < .01$ ) than the three disability groups. Bonferroni tests confirmed this. The RD and MD groups had similarly weak performance on MFl. Both single disability groups had significantly better performance on MFl. ( $t(219) = 2.55, p < .011$ ) than the RD+MD group.

*RAN Digits (RAN:D) and RAN Letters (RAN:L)*

Table 5.

*Mean performance and standard deviations for the four groups on RAN:D and RAN:L*

Test	ND (N=72)		RD (N=36)		MD (N=65)		RD+MD(N=60)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
RAN:D Total Time	52.24	10.87	58.58	12.70	50.43	9.66	55.56	19.91
RAN:D Total Correct	99.49	.92	99.36	1.27	99.45	.97	99.28	1.97
RAN:D per sec.	1.97	.37	1.77	.39	2.04	.44	1.93	.51
RAN: L Total Time	49.56	9.63	54.58	12.13	47.12	8.89	53.64	13.64
RAN: L Total Correct	99.01	2.49	97.94	4.4	99.12	1.80	99.06	1.94
RAN: L per sec.	2.06	.4	1.87	.44	2.16	.43	1.93	.41

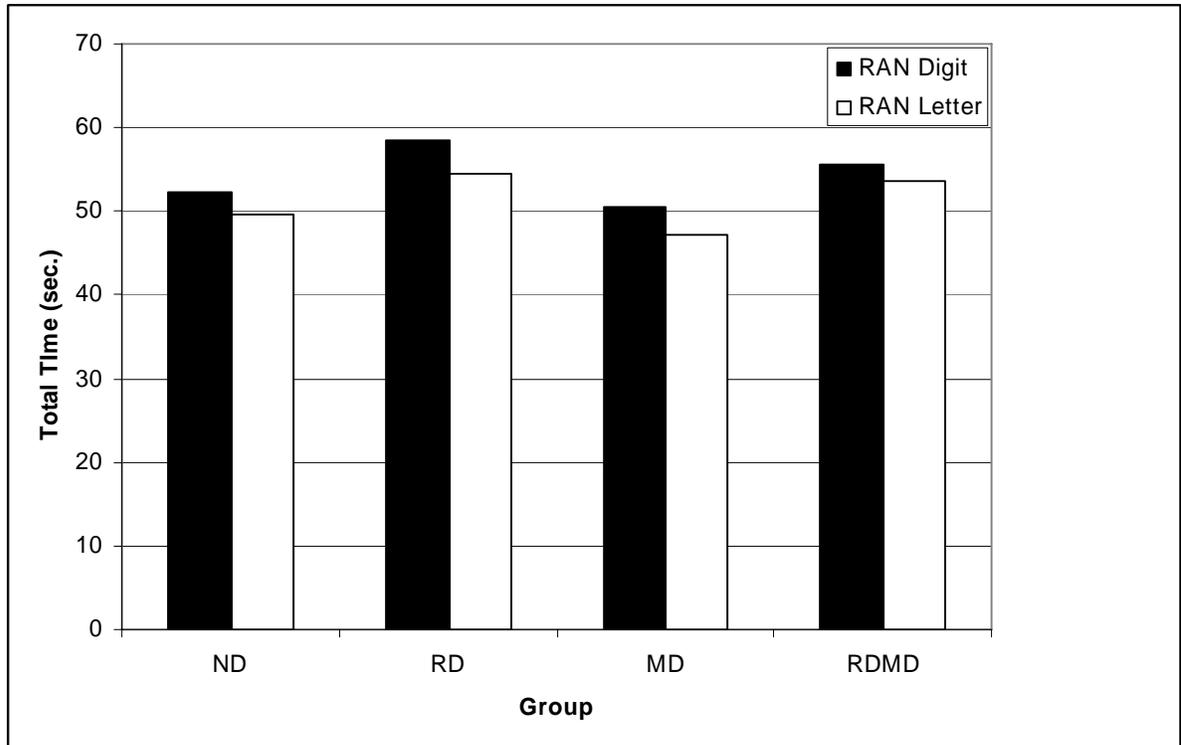


Figure 8. Mean RAN Digits and Letters total time.

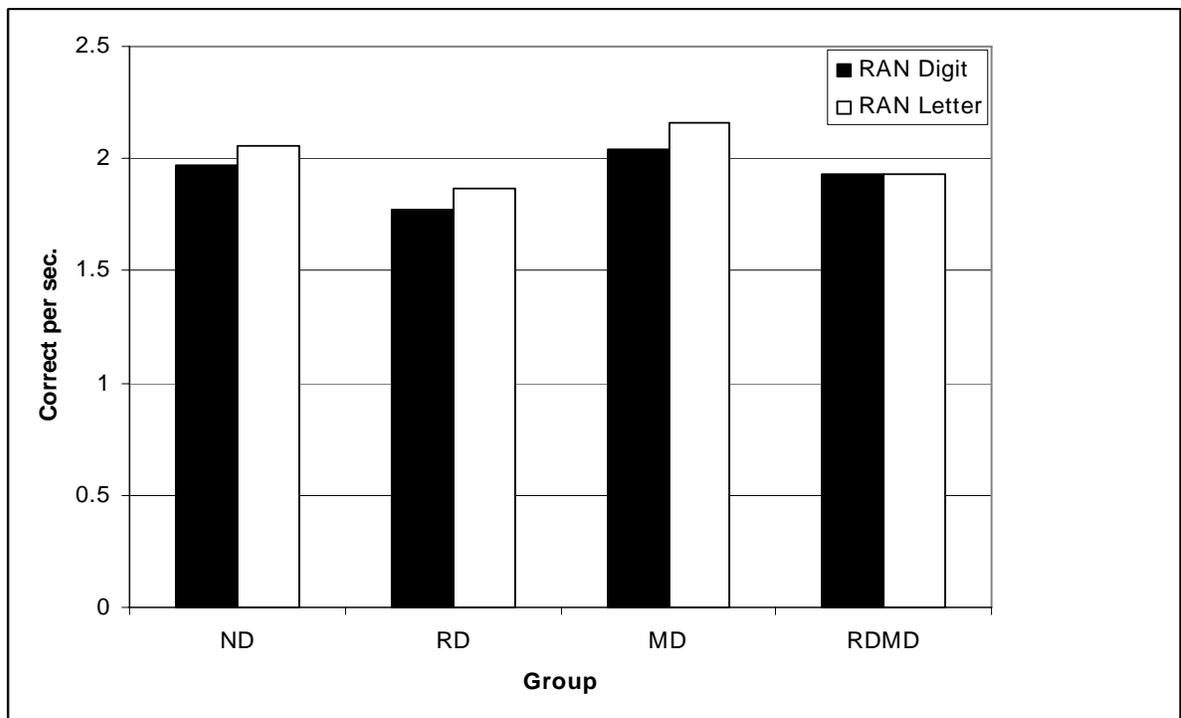


Figure 9. Mean RAN Digits and Letters total correct per sec.

*RAN Letters.* Each groups' mean total time, mean total correct and mean correct per sec. scores can be seen in Table 5. Figure 8 shows mean total time, and Figure 9 demonstrates mean total correct per sec. Assuming equal variance, planned comparisons showed the RD group to have significantly less *accurate* letter naming than the MD group ( $t(219) = -2.16, p < .03$ ). Initial ANOVA comparisons showed significant differences between all four groups' RAN Letters *total time* ( $F(3,222) = 5.35, p < .01$ ), and RAN Letters *per second* (per sec.) ( $F(3,222) = 5.01, p < .002$ ). Using Bonferroni tests, no difference was seen between the ND and MD groups' *total time* and *letters per sec.*, or between the RD and RD+MD groups' *total time* and *letters per sec.* Assuming equal variance, planned comparisons showed the RD group required significantly more *total time* to name Letters ( $t(219) = 3.30, p < .01$ ) than the MD group. Weaker accuracy and need for more time ( $p < .007$ ) both appeared to contribute to the RD group having significantly fewer letters *per sec.* than the MD group ( $p < .005$ ). The need for more time ( $p < .01$ ) appeared to contribute to the RD+MD group having significantly fewer letters *per sec.* than the MD group ( $p < .02$ ).

*RAN Digits.* Each group's mean total time, mean total correct, and mean correct per sec. scores can be seen in Table 5. Figure 8 shows mean total time, and Figure 9 demonstrates mean total correct per sec. Initial ANOVA comparisons did not show group differences on digit naming *accuracy*. Initial ANOVA comparisons showed significant differences between all four groups RAN Digits *total time* ( $F(3,222) = 3.46, p < .02$ ) and RAN digits *per sec.* ( $F(3,219) = 3.36, p < .02$ ). Using Bonferroni tests, no difference was seen between the ND and MD groups' *total time* and *digits per sec.* or between the RD and RD+MD groups *total time* and *letters per sec.* Assuming equal variance, planned comparisons showed the RD group required significantly more *total time* to name Digits

( $t(219) = 2.92, p < .004$ ) than the MD group. The RD group had significantly fewer Digits *per sec.* than the MD group ( $t(219) = -30.86, p < .002$ ). No other significant differences were reported.

*Reading Fluency*

Table 6.

*Mean Performance and Standard Deviations for the Four Groups Total Accuracy, Time, and per sec.(Accuracy/Time) on Benchmark Sight Word List and Exception Words*

	ND (N=72)		RD (N=36)		MD (N=65)		RD+MD(N=50)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Benchmark Accuracy	117.10	3.26	106.92	11.72	117.22	3.32	102.92	18.61
Benchmark Time	83.86	16.48	127.50	67.43	87.66	25.47	113.41	53.08
Benchmark per sec.	1.45	.31	1.00	.39	1.44	.37	1.05	.39
Exception Accuracy	85.52	9.04	66.75	15.60	85.89	10.22	64.00	19.49
Exception Total Time	101.47	26.31	147.47	86.66	110.98	44.01	143.08	77.38
Exception per sec.	.91	.29	.55	.25	.88	.31	.54	.26

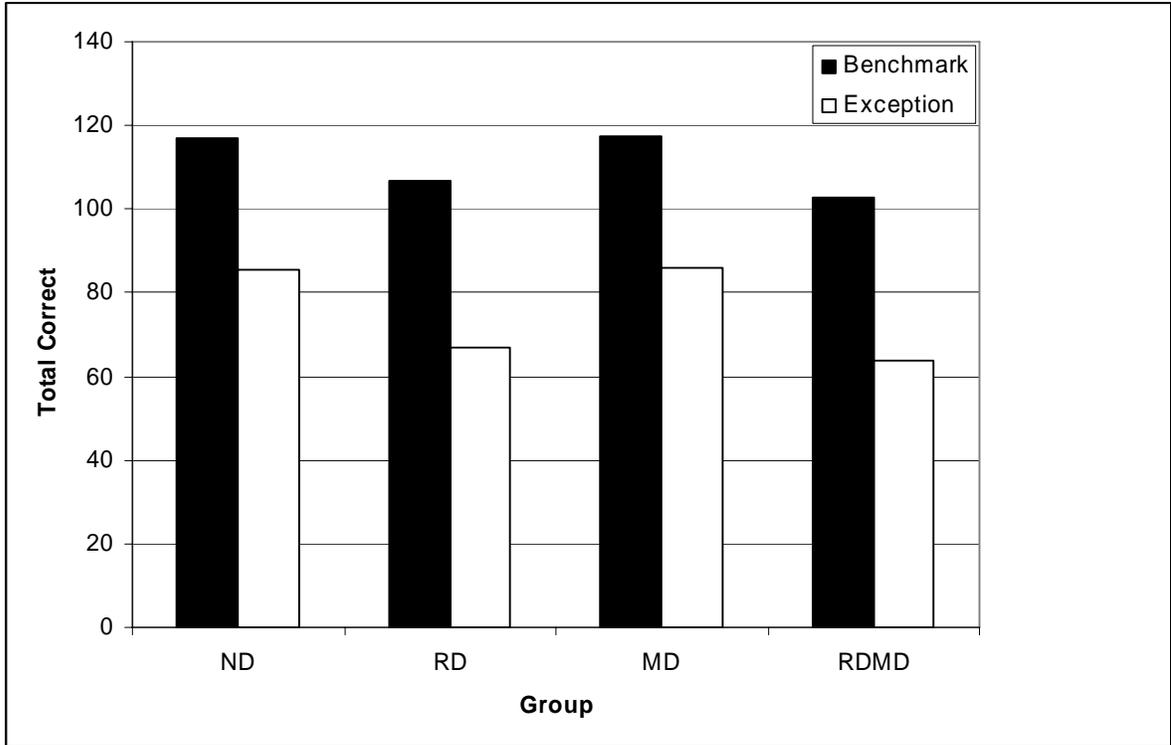


Figure 10. Total correct for Benchmark (total 120) and Exception words (total 108).

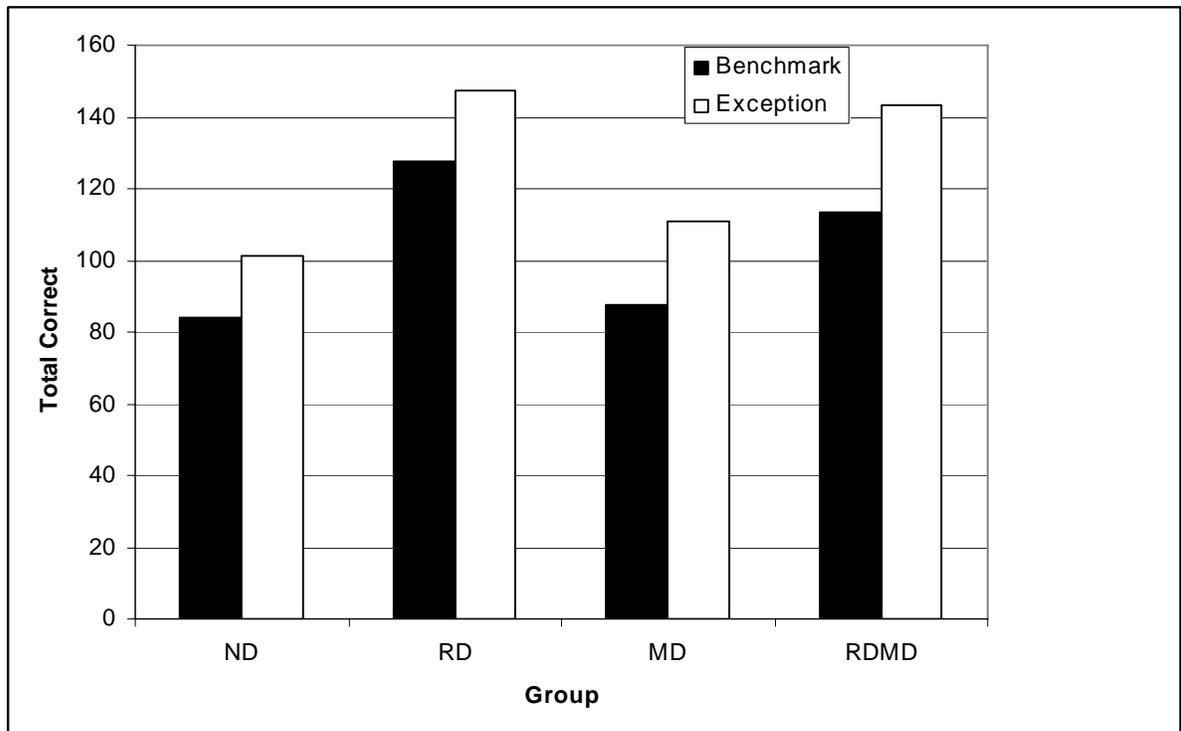


Figure 11. Mean total time on benchmark and exception word lists.

*Reading Fluency: Accuracy, Time, and Words per sec. (Benchmark Word List, and Exception Word List).* All scores can be seen in Table 6. Total time is seen in Figure 10 and mean words per sec. are seen in Figure 11. The Benchmark Word List contains 120 words and the Exception word list contains 108 words.

*Benchmark Accuracy, Total Time, and Words per sec.* Initial ANOVA comparison showed significant differences between all four groups' Benchmark accuracy ( $F(3,221) = 27.24, p < .01$ ), total time ( $F(3,221) = 13.14, p < .01$ ), and words per sec. ( $F(3,221) = 23.34, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group to have significantly higher Benchmark accuracy ( $t(218) = 5.44, p < .01$ ), lower total time (i.e., faster) ( $t(218) = -4.39, p < .01$ ), and more words per sec. ( $t(218) = 5.57, p < .01$ ) than the three disability groups.

*Benchmark Accuracy.* Bonferroni tests showed no significant differences between the ND and MD groups' good accuracy levels and no difference between the RD and RD+MD groups weaker accuracy levels. Bonferroni tests showed the ND and MD group had significantly higher Benchmark accuracy than the RD ( $p < .01$  for both) and RD+MD group ( $p < .01$  for both).

*Benchmark Total Time.* Bonferroni tests showed no significant differences between the ND and MD groups' faster total time and the RD and RD+MD groups' slower total time. Bonferroni tests showed the ND and MD group had significantly faster Benchmark total times than the RD ( $p < .01$  for both) and RD+MD group ( $p < .01$ , and  $p < .01$ , respectively).

*Benchmark Words per sec.* Bonferroni tests showed no significant differences between the ND and MD groups' words per sec. and the RD and RD+MD group's accuracy

levels. Bonferroni tests showed the ND and MD group had significantly higher Benchmark words per sec. than the RD ( $p < .01$  for both) and RD+MD group ( $p < .01$  for both).

*Exception Words Accuracy, Total Time, and Words per sec.* Initial ANOVA comparison showed significant differences between all four groups Exception accuracy ( $F(3,221) = 41.23, p < .01$ ), total time ( $F(3,221) = 8.35, p < .011$ ), and words per second (per sec.) ( $F(3,221) = 26.35, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group to have significantly higher Exception word accuracy ( $t(218) = 6.85, p < .01$ ), lower total time ( $t(218) = -3.88, p < .01$ ), and more words per sec. ( $t(218) = 6.09, p < .01$ ) than the three disability groups. Overall results for Accuracy, Total Time and Words per sec. paralleled the results of the Benchmark test.

*Exception Words Accuracy.* Bonferroni tests showed no significant differences between the ND and MD groups accuracy levels and the RD and RD+MD groups' accuracy levels. Bonferroni tests showed the ND and MD group had significantly higher Exception Word accuracy than the RD ( $p < .01$  for both) and RD+MD group ( $p < .01$  for both).

*Exception Words Total Time.* Bonferroni tests showed no significant differences between the ND and MD groups' total time and the RD and RD+MD groups' total time. Bonferroni tests showed the ND and MD group had significantly faster Exception Word total times than the RD (ND  $p < .01$ ; MD  $p < .05$ ) and RD+MD group (ND  $p < .01$ , and MD  $p < .05$ , respectively).

*Exception Words per sec.* Bonferroni tests showed no significant differences between the ND and MD groups words per sec. and the RD and RD+MD group's accuracy levels. Bonferroni tests showed the ND and MD group had significantly higher Exception Words per sec. than the RD ( $p < .01$  for both) and RD+MD group ( $p < .01$  for both).

*Math Fluency and Math Facts*

Table 7.

*Mean Performance and Standard Deviations for the Four Groups on Experimental Easy and Difficult Math Facts: Addition, Subtraction, Multiplication, and Division*

Correct per sec.	ND (N=72)		RD (N=36)		MD (N=65)		RD+MD (N=50)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Math Fluency	.31	.09	.26	.07	.26	.08	.27	.09
Add Easy Facts	.53	.17	.49	.13	.47	.19	.42	.19
Add Diff. Facts	.25	.01	.23	.08	.21	.09	.19	.10
Subtract Easy Facts	.37	.13	.36	.14	.32	.15	.31	.16
Subtract Diff. Facts	.25	.11	.24	.12	.20	.13	.18	.12
Multiply Easy Facts	.32	.15	.28	.11	.25	.11	.30	.26
Multiply Diff. Facts	.23	.12	.22	.10	.18	.11	.24	.21
Divide Easy Facts	.23	.13	.23	.11	.19	.09	.20	.12
Divide Diff. Facts	.20	.15	.18	.10	.14	.09	.17	.14

*WJ-III Math Fluency.* The WJ-III Math Fluency task has a 3 minute (180 second) time limit. Accuracy scores were calculated by taking the total correct within the specified time limit. Facts per sec. were calculated by dividing the total correct by 180 seconds. Initial ANOVA comparisons showed significant differences between the four groups total accuracy scores ( $F(3, 222) = 4.15, p < .007$ ), and facts per sec. ( $F(3, 222) = 4.15, p < .007$ ). Assuming equal variance, planned comparisons showed the ND group could solve significantly more facts accurately ( $t(219) = 3.45, p < .01$ ) and produced more accurate facts per sec. ( $t(219) =$

3.45,  $p < .01$ ) than the three disability groups. The three disability groups did not have significantly different total accuracy or facts per sec. scores, but all appeared similarly weaker than the ND group. Bonferroni tests, at the .02 level, showed the ND group to have significantly higher accuracy and facts per sec. (both  $p = .012$ ). The RD, MD, and RD+MD groups appeared similarly weak in their mean facts per sec.

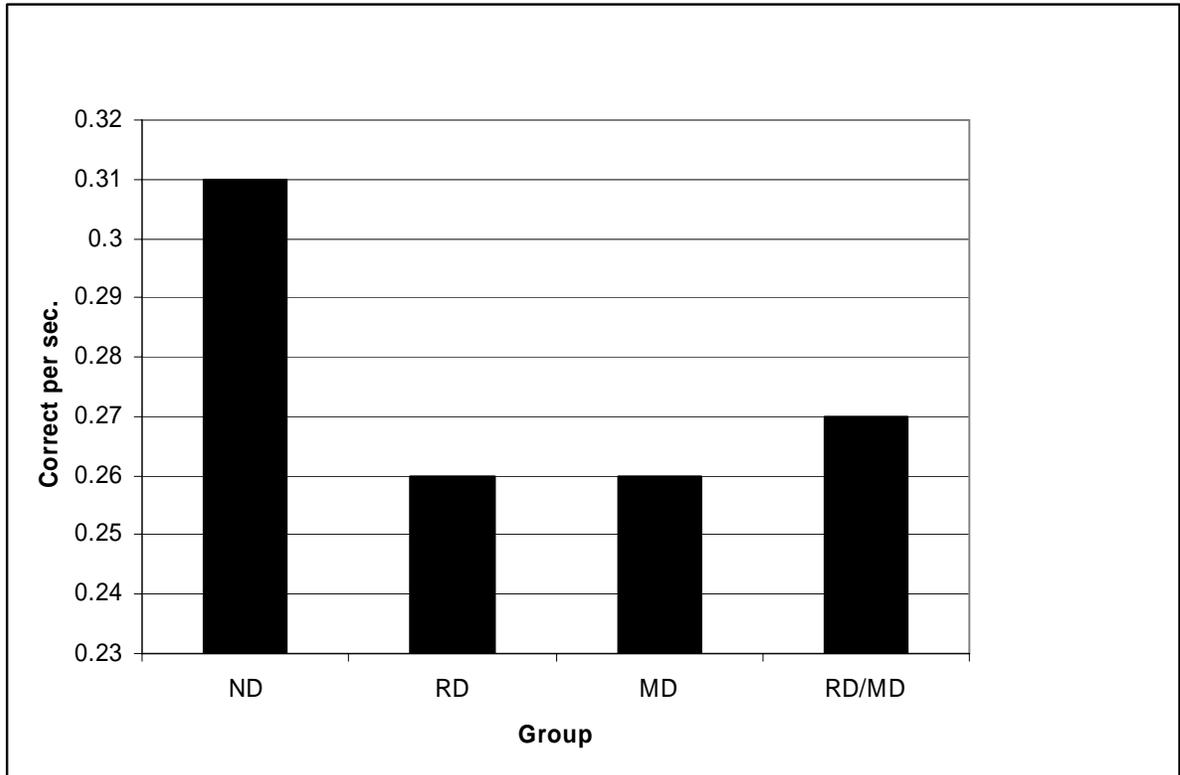
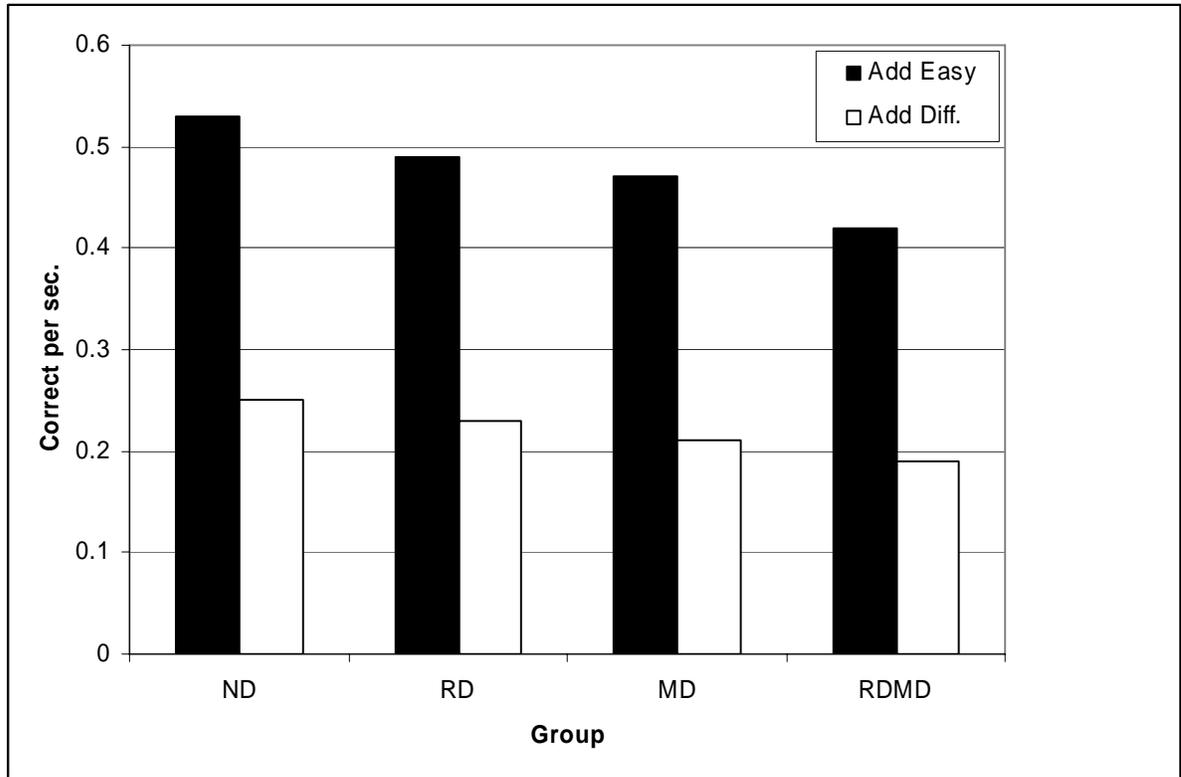


Figure 12. Mean correct facts per sec. on WJ-III Math Fluency

*Unstandardized Easy and Difficult Addition Facts*

*Easy Addition Facts.*



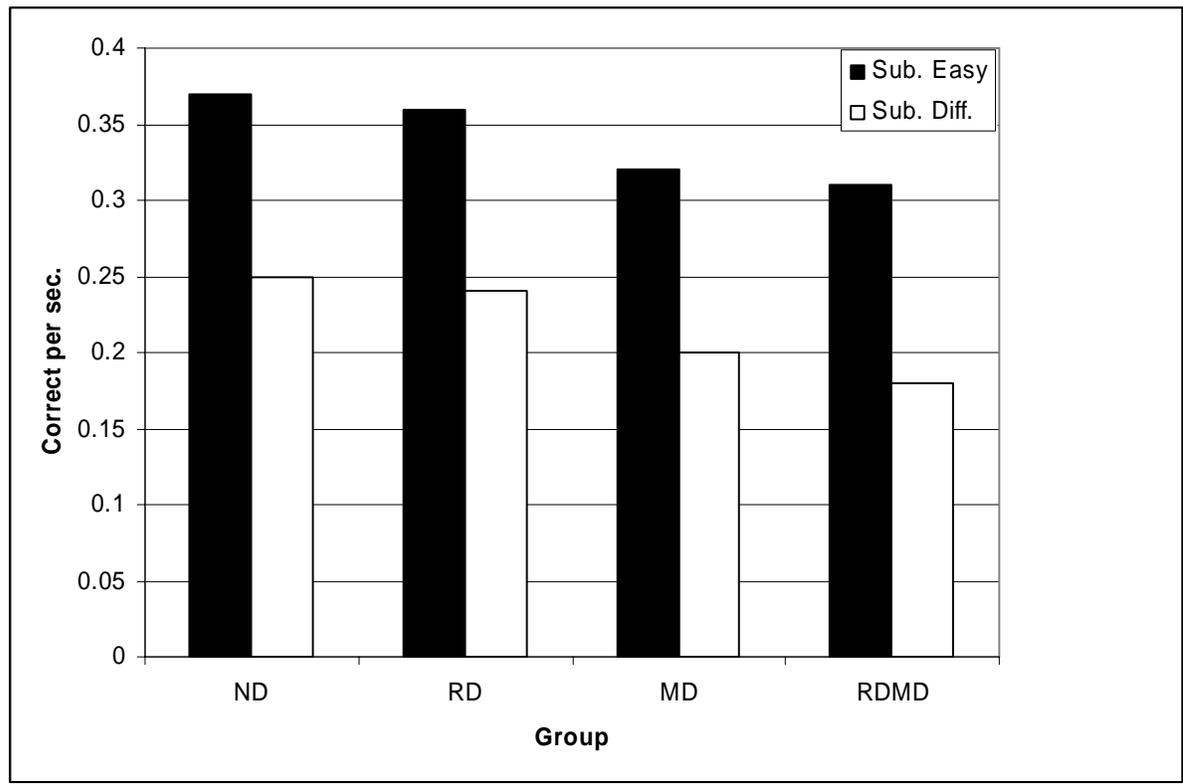
*Figure 13.* Mean facts per sec. on easy addition (Add Easy) and difficult addition (Add Diff.) facts

ANOVA comparisons showed significant differences between the four groups total accuracy scores for Easy Addition accuracy ( $F(3, 222) = 3.84, p < .01$ ), total time ( $F(3, 222) = 4.44, p < .005$ ), and facts per second (per sec.) ( $F(3, 222) = 3.84, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group could solve significantly more easy addition facts accurately ( $t(219) = 2.37, p < .05$ ) and more quickly ( $t(219) = -2.81, p < .01$ ), producing more accurate facts per sec. ( $t(219) = 2.77, p < .01$ ) than the three disability groups. The RD and MD groups did not significantly differ from each other in accuracy, speed or facts per sec. The RD and MD groups solved significantly more facts than the RD+MD

groups ( $t(219) = 2.24, p < .03$ ). Further Bonferroni tests, at the .02 level, showed the ND group to have significantly more easy add facts per sec. than the RD+MD group ( $p < .01$ ).

*Difficult Addition Facts.* Initial ANOVA comparisons showed significant differences between the 4 groups total accuracy scores for Difficult Addition accuracy ( $F(3, 220) = 3.73, p < .01$ ), total time ( $F(3, 220) = 3.2, p < .03$ ), and facts per second (per sec.) ( $F(3, 220) = 5.79, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group could solve significantly more difficult addition facts accurately ( $t(217) = 2.4, p < .02$ ), but not more quickly ( $t(217) = -1.84$ ), producing more accurate facts per sec. ( $t(217) = 3.33, p < .01$ ) than the three disability groups. The RD and MD groups did not significantly differ from each other in accuracy, speed, or facts per sec. While the RD and MD groups were not more accurate than the RD+MD group ( $t(219) = 1.33$ ) the RD and MD groups were significantly faster than the RD+MD group ( $t(219) = -2.42, p < .02$ ), and solved more difficult addition facts per sec. than the RD+MD group ( $t(217) = 2.11, p < .04$ ). Further Bonferroni tests, at the .02 level, showed the ND group to have significantly more easy add facts per sec. than the RD+MD group ( $p < .01$ ).

*Unstandardized Easy and Difficult Subtraction Facts*



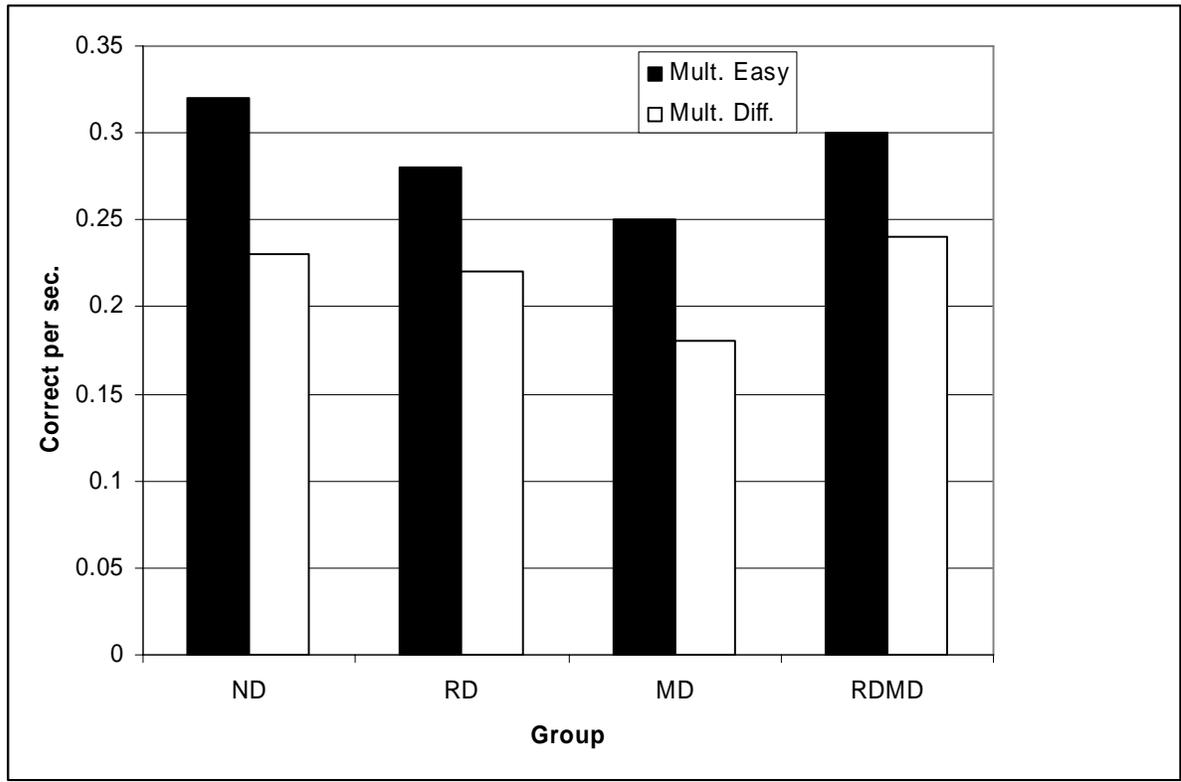
*Figure 14. Mean facts per sec. on easy subtraction (Sub. Easy) and difficult subtraction (Sub. Diff.) facts*

*Easy Subtraction Facts.* ANOVA comparisons showed significant differences between the four groups total accuracy scores for Easy Subtraction total time ( $F(3, 221) = 2.96, p < .04$ ), and facts per second (per sec.) ( $F(3, 221) = 2.61, p < .06$ ). Assuming equal variance, planned comparisons showed the ND group could solve significantly more easy subtraction facts accurately ( $t(218) = 2.24, p < .03$ ) and more quickly ( $t(218) = -2.16, p < .03$ ); producing more accurate facts per sec. ( $t(218) = 2.21, p < .03$ ) than the three disability groups. Planned comparisons showed that the ND group produced more automatic easy subtraction facts (e.g. total correct in  $< 1$  second) than the three disability groups ( $t(218) = 1.99, p < .05$ ). The RD and MD groups did not significantly differ from each other in accuracy, speed or

facts per sec. No significant differences were found between the single disability and the RD+MD group for easy subtraction facts.

*Difficult Subtraction Facts.* Initial ANOVA comparisons showed significant differences between the four groups accuracy for Difficult Subtraction facts ( $F(3, 220) = 7.29, p < .01$ ), and facts per sec. ( $F(3,220) = 4.83, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group could solve significantly more difficult subtraction facts accurately ( $t(217) = 3.63, p < .01$ ), but not more quickly ( $t(217) = -.776$ ); producing more accurate facts per sec. ( $t(217) = 2.86, p < .01$ ) than the three disability groups. Bonferroni tests, at the .02 level, specified that the ND group had more accurate answers than the MD group ( $p = .02$ ) and the RD+MD group ( $p < .01$ ). Bonferroni tests, at the .02 level, specified that the ND group produced more accurate answers to difficult subtraction facts requiring processing/working memory (e.g. total correct in  $> 1$  second) than the RD+MD group ( $p < .01$ ). The RD group had more accurate answers than the RD+MD group ( $p = .05$ ). The ND group had more difficult subtraction answers per sec. than the RD+MD group ( $p < .01$ ). The RD and MD groups did not significantly differ from each other in accuracy, speed or facts per sec. The RD and MD groups were more accurate than the RD+MD group ( $t(217) = 2.54, p < .01$ ) but they did not differ in time or number of correct facts per sec.

*Unstandardized Easy and Difficult Multiplication Facts*



*Figure 15.* Mean facts per sec. on easy multiplication (Mult. Easy) and difficult multiplication (Mult. Diff.) facts.

*Easy Multiplication Facts.* ANOVA comparisons showed significant differences between the four groups total accuracy scores for Easy Multiplication ( $F(3, 219) = 5.05$ ,  $p < .01$ ), and facts per second (per sec.) ( $F(3, 219) = 2.50$ ,  $p < .06$ ), but not for total time. Assuming equal variance, planned comparisons showed the ND group could solve significantly more easy multiplication facts accurately ( $t(216) = 3.27$ ,  $p < .01$ ) but not more quickly; producing more accurate facts per sec. ( $t(216) = 1.96$ ,  $p < .05$ ) than the three disability groups. Bonferroni tests, at the .02 level, showed that the ND group produce more accurate easy multiplication facts than the MD group ( $p < .01$ ) and the RD+MD group ( $p < .01$ ). The ND group produced more easy multiplication facts per sec. than the MD group

( $p < .05$ ) and more easy multiplication facts requiring processing/working memory (e.g. total correct in  $> 1$  second) than the RD+MD group ( $p < .01$ ).

The RD and MD groups did not significantly differ from each other in accuracy, speed or facts per sec. No significant differences were found between the single disability and the RD+MD group for easy multiplication facts. All appeared similarly weaker.

*Difficult Multiplication Facts.* Initial ANOVA comparisons showed significant differences between the four groups accuracy for difficult multiplication facts ( $F(3, 213) = 7.56, p < .01$ ), and just reached significance for total time ( $F(3, 213) = 2.65, p < .05$ ).

Assuming equal variance, initial planned comparisons showed the ND group could solve significantly more difficult multiplication facts accurately ( $t(216) = 3.27, p < .01$ ), but not more quickly ( $t(216) = .321$ ); producing more accurate facts per sec. than the three disability groups ( $t(216) = 1.96, p < .05$ ). Planned comparisons showed no significant difference between the RD, MD, and RD+MD groups' accuracy, speed, or facts per sec.

Planned comparison showed that the ND group produced more accurate automatic easy multiplication facts (e.g. total correct in  $< 1$  second) than the three disability groups ( $t(216) = 1.93, p < .05$ ). Planned comparison also showed that the ND group produced significantly more accurate answers to difficult multiplication facts requiring processing/working memory (e.g. total correct in  $> 1$  second) than the three disability groups ( $t(210) = 3.16, p < .01$ ). Bonferroni tests, at the .02 level, specified that the ND group solved more difficult multiplication facts requiring processing/working memory than the RD+MD group ( $p < .01$ ).

An initial planned comparison showed that the RD group solved more difficult multiplication facts accurately ( $< 1$  sec) than the MD group  $t(210) = 2.73, p < .01$ . Initial

planned comparisons comparing RD and MD to the RD+MD group showed the two single disability groups produced significantly more accurate answers to difficult multiplication facts requiring processing/working memory (e.g. total correct in > 1 second) than the RD+MD group ( $t(210) = 2.37, p < .02$ ).

*Division Facts Easy and Difficult.* Given that this sample of students was mainly in Grade 4, division was just being taught; division is more of an Ontario Math Curriculum focus in Grade 5. Thus, the the number of children in each group who could complete the easy division facts dropped significantly (ND = 42/72, RD = 25/36, MD = 36/65, and RD+MD = 30/50). The sample size dropped further for the difficult division facts (ND = 37/72, RD = 22/36, MD = 31/65, and RD+MD = 25/50). For this study the multiplication facts were used as the highest level of math fact comparison.

*Working Memory Span, Phonological Processing, and Algorithmic Processing.*

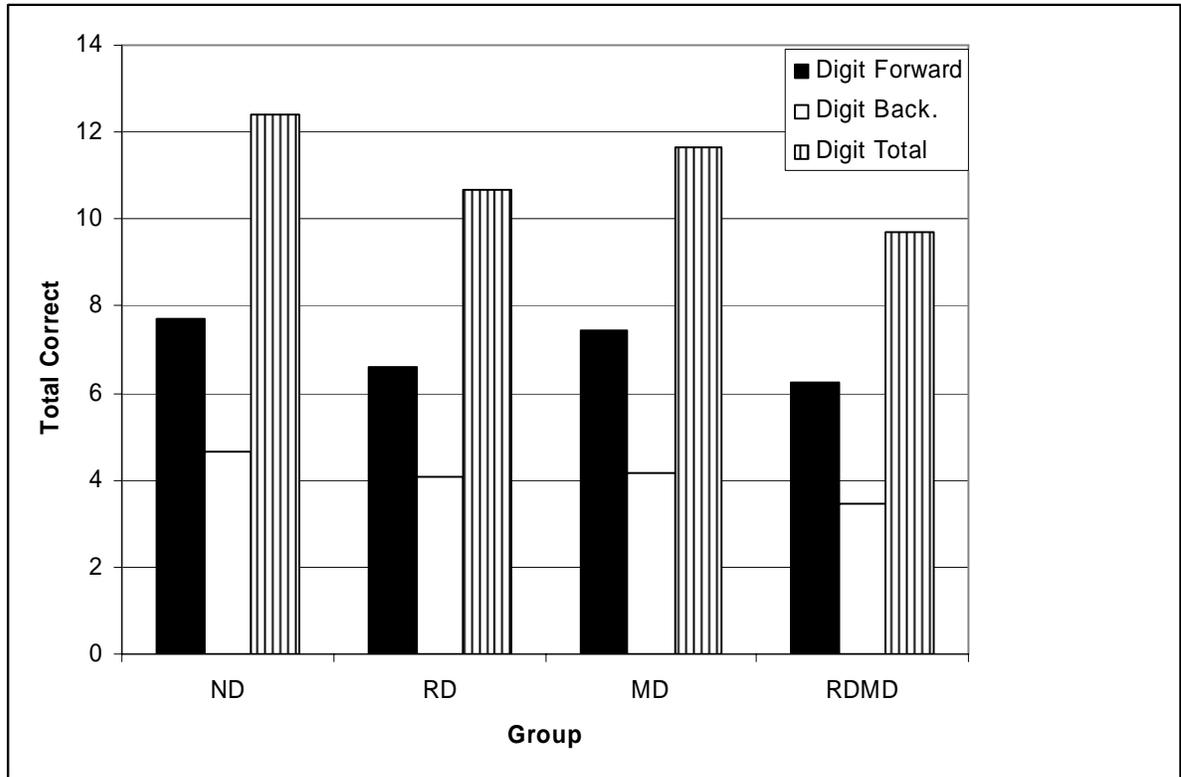
Table 8.

*Mean Performance and Standard Deviations for the Four Groups on the WISC-III Digit Span Task, and Experimental Letter Span Task*

Test	ND (N=72)		RD (N=36)		MD (N=65)		RD+MD (N=50)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Digit Span Forward	7.72	1.53	6.61	1.13	7.45	1.71	6.24	1.20
Digit Span Backward	4.67	1.23	4.08	1.16	4.18	1.18	3.46	1.20
Digit Span Total	12.39	2.15	10.69	1.64	11.63	2.30	9.7	1.82
Digit Span Scaled Score	9.13	2.25	7.25	1.75	7.91	2.11	5.74	1.52
Letter Span Forward	6.65	1.42	5.31	1.17	6.09	1.29	5.32	1.13
Letter Span Backward	3.49	1.22	2.92	.91	3.28	1.08	2.72	1.14
Letter Span Total	10.15	2.04	8.22	1.38	9.38	1.85	7.98	1.82

*Digit and Letter Span*

*Digit Span.*



*Figure 16.* Mean Total Correct on WISC-III Digit Forward, Digit Backward (Digit Back.), and Digit Total.

ANOVA comparisons showed differences between the four groups scores for Digits Forward total ( $F(3,222) = 12.64, p < .01$ ), Digits Backwards total ( $F(3,222) = 10.02, p < .01$ ), and Digit Span total ( $F(3,222) = 18.53, p < .01$ ). Assuming equal variance, planned comparisons showed the ND to have significantly higher digits forward total ( $t(219) = 4.52, p < .01$ ), digits backward total ( $t(219) = 4.37, p < .01$ ), and digit span total ( $t(219) = 5.78, p < .01$ ). Bonferroni tests specified that the ND group had significantly higher Digit Span standard scores than the RD group ( $p < .01$ ), the MD group  $p = .003$ , and the RD+MD group ( $p < .01$ ). Using total correct, Bonferroni tests at the .02 level, specified that the ND group

recalled more digits forward than the RD group ( $p < .01$ ), and the RD+MD group ( $p < .01$ ).

The ND and MD group did not appear to differ. No specified differences in Digits

Backwards were found. The ND group had a significantly higher Digit Span Total than the

RD group ( $p < .01$ ), and the RD+MD group ( $p < .01$ ).

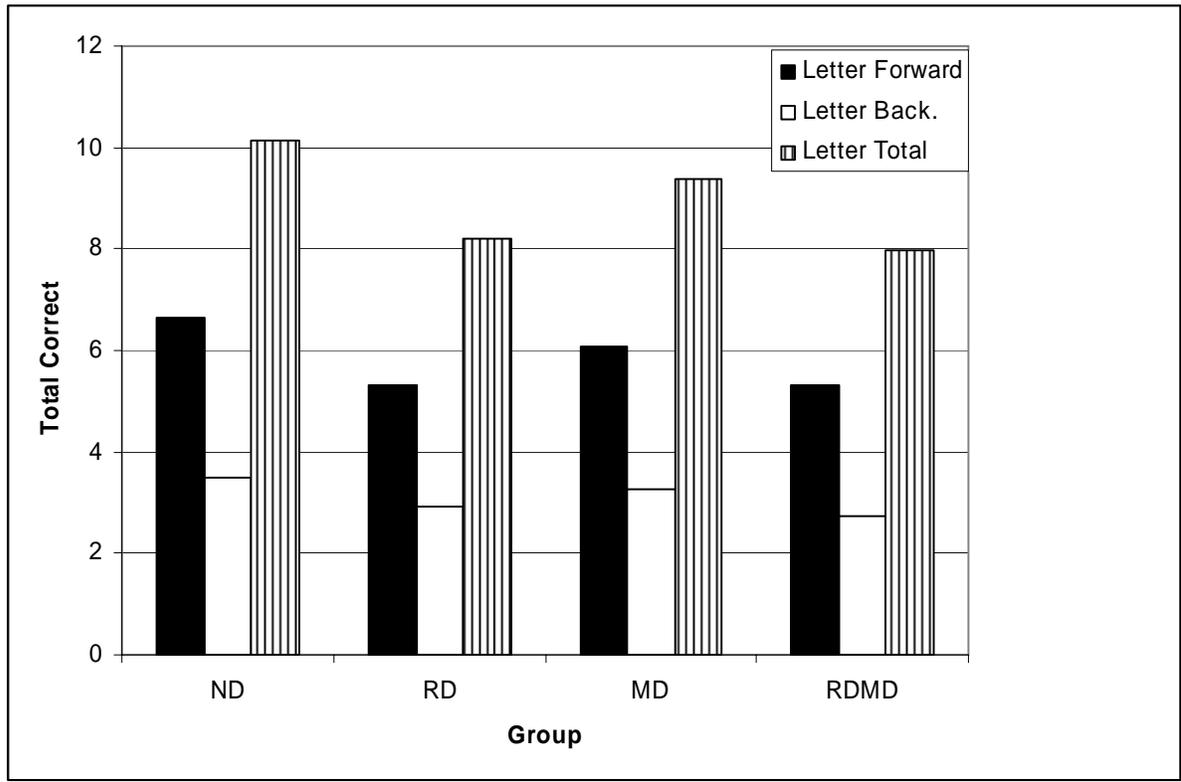
In terms of standard scores, the RD and MD group did not significantly differ and the RD group and the MD group, both higher standard score than the RD+MD group ( $p < .01$ ).

Initial planned comparison showed that the MD group had significantly higher digits forward total ( $t(219) = -2.75, p < .01$ ), and digit span total ( $t(219) = -2.20, p < .03$ ) than the RD group.

The MD and RD group were similar on digits backwards total. Planned comparisons showed the single disability groups to have significantly higher digits forward total ( $t(219) = 3.07, p < .01$ ), digits backward total ( $t(219) = 3.20, p < .01$ ), and digit span total ( $t(219) = 4.07, p < .01$ ) then the RD+MD group.

Bonferroni tests, at the .02 level, specified that the MD group had a higher Digit Span Total than the RD+MD group ( $p < .01$ ).

*Letter Span.*



*Figure 17.* Mean Total Correct on Letter Forward, Letter Backward (Letter Back.), and Letter Total.

ANOVA comparisons showed differences between the four groups scores for Letters Forward ( $F(3,221) = 14.51, p < .01$ ), Letters Backwards ( $F(3,220) = 5.53, p < .01$ ), and Letter Span ( $F(3,220) = 17.13, p < .01$ ). Assuming equal variance, planned comparisons showed the ND to have significantly higher letters forward ( $t(219) = 5.82, p < .01$ ), letters backward ( $t(219) = 3.21, p < .01$ ), and letter span ( $t(219) = 6.08, p < .01$ ). Bonferroni tests specified that the ND group produced more letters forward than the RD and the RD+MD group ( $p < .01$ ); more letters backwards than the RD+MD group ( $p < .01$ ), and had a higher letter total than the RD and RD+MD group ( $p < .01$ ).

Planned comparisons showed that similar to the WISC-IV digit span results the MD group had significantly higher letters forwards ( $t(219) = -2.95, p < .01$ ) and significantly higher letter span ( $t(219) = -3.01, p < .01$ ) than the RD group. Comparable to digit span, planned comparisons showed the RD and MD groups to have significantly higher letter span ( $t(219) = 4.07, p < .01$ ) than the RD+MD group. Also, similar to digit span, the MD and RD group were similar on letters backwards. Bonferroni tests specified that the MD group produced more letters forward than the RD ( $p < .01$ ) and the RD+MD group ( $p = .01$ ). The MD group produced more letters backwards ( $p < .05$ ). In terms of letter span total, Bonferroni tests specified that the MD group had a higher total than the RD group ( $p < .01$ ) and the RD+MD group  $p < .01$

*Phonological Processing*

Table 9.

*Mean Total and Scaled Scores and Standard Deviations for the Four Groups on*

*Phonological Processing Subtests: Elision and Nonword Repetition from the CTOPP*

CTOPP Test	ND (N=72)		RD (N=36)		MD (N=65)		RD+MD(N=50)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Elision Total	15.4	3.46	11	4.15	14.48	4.07	9.48	4.19
Elision Scaled Score	10.43	2.33	7.44	2.41	9.63	2.43	6.26	2.33
Nonword Repetition	8.32	2.40	7.00	2.81	8.55	3.17	6.68	2.57
Total								
Nonword Repetition	7.58	1.83	6.57	2.40	7.68	2.43	6.06	1.95
Scaled Score								

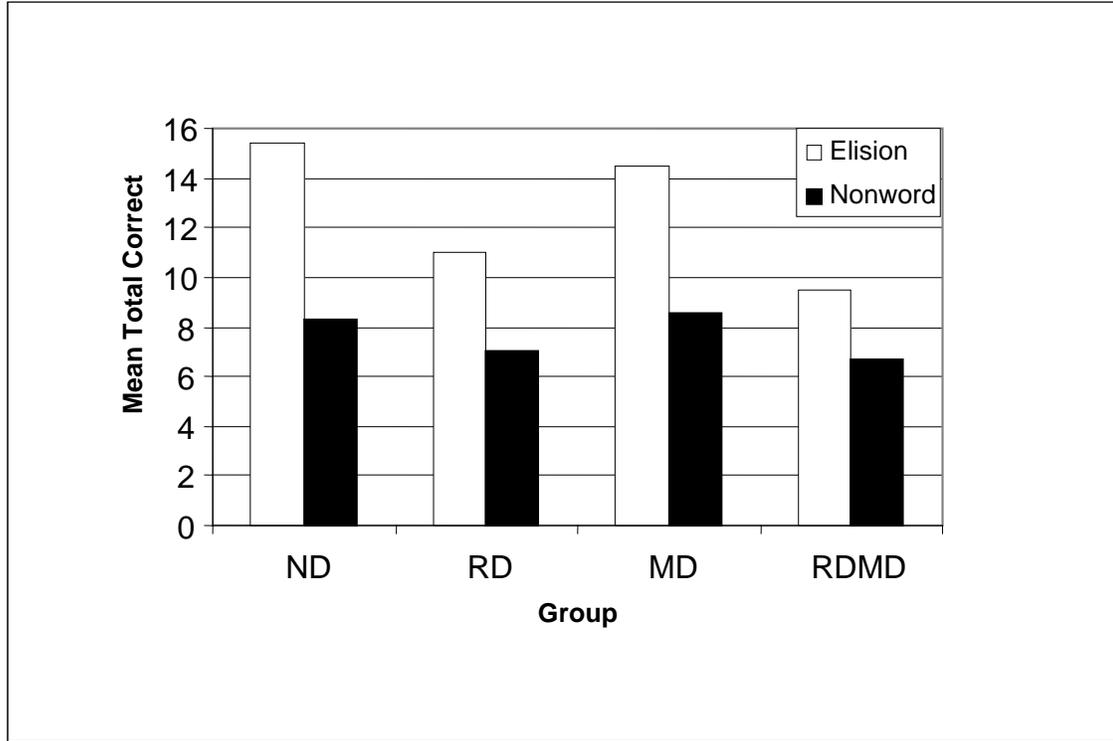


Figure 18. Scaled scores for CTOPP Elision and Nonword Repetition (Nonword).

*Elision scaled scores.* ANOVA comparisons showed differences between the four groups scores for Elision standard scores ( $F(3,222) = 36.99, p < .01$ ). Assuming equal variance, planned comparisons showed the ND to have significantly higher Elision ( $t(219) = 7.73, p < .01$ ) than the three disability groups. Bonferroni, at the  $p = .02$  level, specified that the ND group scored higher than the RD and the RD+MD group ( $p < .01$ ) for both but not the MD group. Planned comparisons showed that the MD group had significantly higher Elision ( $t(219) = -4.44, p < .01$ ) than the RD group. The Bonferroni test specified that the MD group had a higher standard score than the RD group and the RD+MD group both at ( $p < .01$ ), and the RD group had a higher scaled score than the RD+MD group ( $p < .01$ ).

*Nonword Repetition Standard Scores:* ANOVA comparisons showed differences between the four groups scores for Nonword Repetition ( $F(3,220) = 7.58, p < .01$ ). Assuming equal

variance, planned comparisons showed the ND to have significantly higher Nonword Repetition ( $t(217) = 2.62, p < .01$ ) than the three disability groups. Bonferroni, at the .02 level, specified that the ND group had a higher standard score than the RD+MD group ( $p = .01$ ). Planned comparisons showed the MD group had significantly higher Nonword Repetition ( $t(217) = -2.49, p < .02$ ) than the RD group. Planned comparisons showed that together the single disability groups showed significantly higher Nonword Repetition ( $t(217) = 2.86, p < .01$ ) than the RD+MD group. The Bonferroni test confirmed that the MD group performed better than the RD+MD group and similar to the RD group.

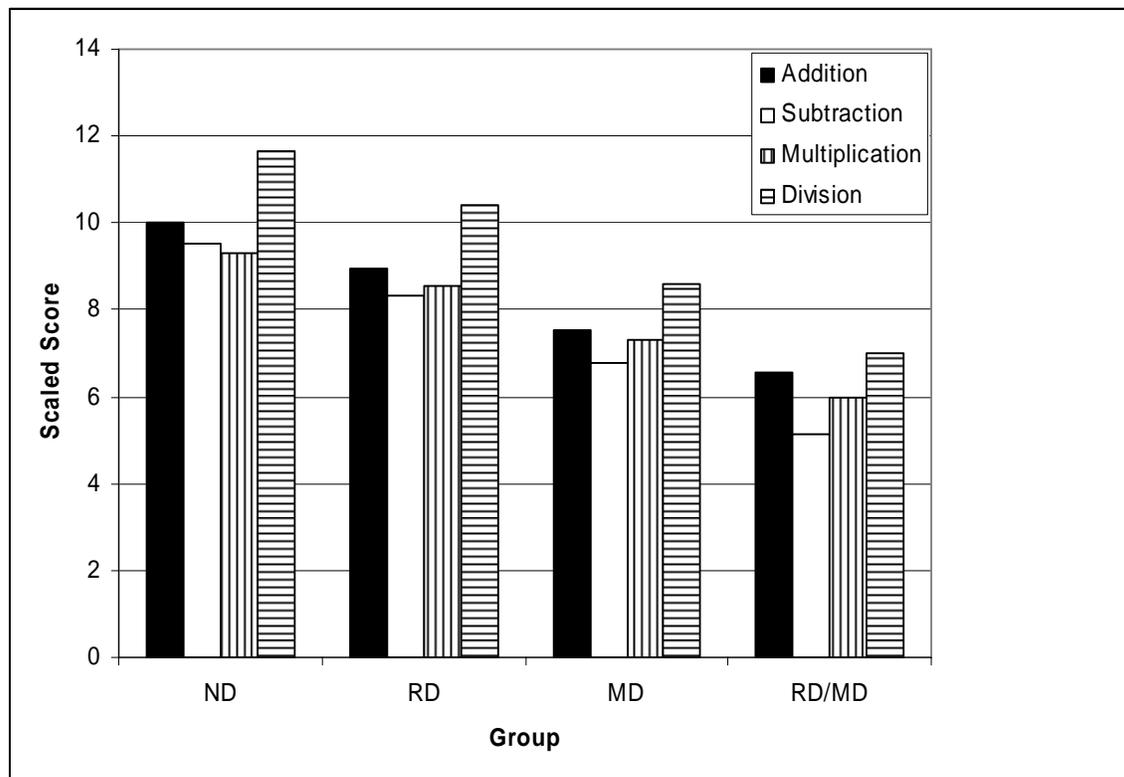
*Algorithmic Processing*

Table 10.

*Mean Scaled Score Performance and Standard Deviations for the four groups on the KeyMath-Revised Operations Subtests: Addition, Subtraction, Multiplication, and Division*

KeyMath-R Test	ND (N=72)		RD (N=36)		MD (N=65)		RD+MD(N=50)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Addition	10.01	2.30	8.97	2.59	7.52	2.87	6.56	2.61
Subtraction	9.52	2.53	8.34	2.53	6.78	2.71	5.16	1.48
Multiplication	9.31	2.20	8.57	2.42	7.32	2.54	6.00	2.05
Division	11.66	2.27	10.40	2.34	8.58	3.02	7.00	2.95

*KeyMath Revised, Algorithms: Addition, Subtraction, Multiplication, and Division*



*Figure 19.* Mean Total Correct on KeyMath-Revised Operations: Addition, Subtraction, Multiplication, and Division.

*Addition.* Table 10 and Figure 19 show mean scaled scores on Addition. ANOVA comparisons showed differences between the four groups standard scores for Addition algorithms ( $F(3,221) = 20.54, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group scored significantly higher than the three disability groups ( $t(218) = 6.18, p < .01$ ). Bonferroni tests, at the .02 level, specified that the ND group scored significantly higher than the MD and the RD+MD group ( $p < .01$ ), with no significant difference between the ND and RD groups. Planned comparisons demonstrated that the RD group scored significantly higher than the MD ( $t(218) = 2.69, p < .01$ ). Bonferroni tests

confirmed that the RD group had higher standard scores than the MD group ( $p < .05$ ). The RD group had higher scores than the RD+MD group  $p < .01$ . The MD and RD+MD groups had similarly weak scores.

*Subtraction.* Table 10 and Figure 19 show mean scaled scores on Subtraction. ANOVA comparisons showed differences between the four groups standard scores for Subtraction algorithms ( $F(3,220) = 36.23, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group scored significantly higher than the three disability groups ( $t(217) = 7.93, p < .01$ ). Bonferroni tests specified that the ND group scored significantly higher than the MD and the RD+MD group  $p < .01$ , with no significant difference between the ND and RD group. Planned comparisons demonstrated that the RD group scored significantly higher than the MD ( $t(217) = 3.14, p < .01$ ). Bonferroni tests confirmed that the RD group had higher standard scores than the MD group ( $p < .01$ ), and the RD+MD group ( $p < .01$ ). The MD and RD+MD groups both showed weak performance on addition algorithms. On subtraction algorithms the MD group were weaker than the ND and RD group but stronger than the RD+MD group ( $p < .01$ ).

*Multiplication.* Table 10 and Figure 19 show mean scaled scores on Multiplication. ANOVA comparisons showed differences between the four groups standard scores for Multiplication algorithms ( $F(3,220) = 22.44, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group scored significantly higher than the three disability groups ( $t(217) = 5.99, p < .01$ ). Bonferroni tests, at the .02 level, specified that the ND group scored significantly higher than the MD and the RD+MD group ( $p < .01$ ), with no significant difference to the RD group. Planned comparisons demonstrated that the RD group scored significantly higher than the MD ( $t(217) = 2.58, p < .01$ ). Bonferroni tests

confirmed that the RD group had higher standard scores than the MD group ( $p < .01$ ), and the RD+MD group ( $p < .01$ ). The RD+MD group were weaker than the ND, RD, and the MD group ( $p < .01$ ).

*Division.* Table 10 and Figure 19 show mean scaled scores on Division ANOVA comparisons showed differences between the four groups standard scores for Division algorithms ( $F(3,220) = 33.85, p < .01$ ). Assuming equal variance, planned comparisons showed the ND group scored significantly higher than the three disability groups ( $t(217) = 7.70, p < .01$ ). Bonferroni tests, at the .02 level, specified that the ND group scored significantly higher than the RD ( $p < .01$ ), MD and the RD+MD group ( $p < .01$ ). Planned comparisons demonstrated that the RD group scored significantly higher than the MD ( $t(217) = 2.58, p < .01$ ). Bonferroni tests confirmed that the RD group had higher standard scores than the MD group ( $p < .01$ ), and the RD+MD group ( $p < .01$ ). The RD+MD group performed more poorly than the ND and RD group ( $p < .01$ ) and the MD group ( $p < .01$ ).

## Discussion

### *WASI IQ and Executive Function*

The first purpose of the present research was to investigate the type and extent of cognitive processing deficits in single (RD and MD) and comorbid (RD+MD) learning disability groups on tasks measuring IQ, ‘executive’ function, automatic processes (e.g., RAN, words, and math facts), working memory span, phonological processing, and algorithmic processing.

While the present study selected students with average overall ‘VIQ/PIQ’ (i.e., expressive vocabulary, verbal/nonverbal reasoning, and visual-spatial ability) and significantly weaker performance on reading and math achievement tests, it is acknowledged

that a discrepancy of any nature needs empirical support to explicate underlying cognitive processing deficit(s) involved in reading, math, or comorbid reading/math disabilities. In the current study, each group was assessed on ‘IQ’ and ‘executive function’ tests measuring visual-spatial analysis (e.g., Block Design and Planning), expressive Vocabulary, verbal reasoning (e.g., Similarities), and nonverbal reasoning (e.g., Matrix Reasoning and Concept Formation).

On tests of visual-spatial analysis, the performance of all groups fell within age-level expectations, and no significant differences were found. The ND group had higher expressive Vocabulary and verbal and nonverbal reasoning than both poor reader groups (RD and RD+MD). Single disability groups (RD and MD) had similar expressive Vocabulary with it being significantly better than that of the comorbid group (RD+MD). The good readers (ND and MD) were equivalent in their good verbal reasoning which was significantly stronger than that of the poor readers (RD and RD+MD). In terms of ‘executive’ nonverbal reasoning (i.e., Matrix Reasoning and Concept Formation), the ND, RD, and MD groups were significantly better than the comorbid RD+MD group.

#### *Reading and Math Achievement*

Using age-based norms, the WJ-III Tests of Achievement classify average age-level expectations as standard scores falling within the 90 to 110 range. On LWID and WA scores, the good readers (ND and MD) demonstrated reading skills superior to the poor readers (RD and RD+MD). By age norms, the good readers’ mean performances fell solidly within age norm expectations. The poor readers’ mean performances fell below age norm expectations.

As defined by their Calculation scores, good mathematicians (ND and RD) exhibited superior math skills to the poor mathematicians (MD and RD+MD). By age norms, the good mathematicians' mean performances fell solidly within age norm expectations. The poor mathematicians' mean performances fell well below age norm expectations, both groups being very weak in math Calculation. Poor mathematicians (MD and RD+MD) were defined as being significantly weaker solely on their Calculation performance alone, and Applied Problems and Math Fluency subtests were used as dependant measures.

On Applied Problems, the ND, RD, and MD groups' mean scores fell within age level expectations, with the RD+MD group falling just below age level expectations on Applied Problems. While this pattern might be expected given the reading and math weaknesses of the comorbid group, two other issues with Applied Problems should be noted. Relative to skill level demands of the Ontario Math Curriculum, the Applied Problems test appeared to overestimate the children's performance. One feature of the test that could have facilitated age level performance is that children were provided with visual aids and a pencil and paper, with no stated time limit, to figure out each problem. Visual aids and time are both tools that psychologists recommend to help enhance math learning for children with a math learning disability. In addition to potentially inflated scores, all groups may have benefited from specific accommodations offered on this task (e.g., visual aids, and pen and rough paper with no time limit) that could add potential confounds when used as a diagnostic measure.

The third math achievement test that was administered was the Math Fluency test. Statistically, the ND group met age level expectations and had significantly higher scores on Math Fluency than the three disability groups. While all disability groups' performance fell

below age level expectations, the comorbid RD+MD group performed more poorly on this test than the single disability groups. In the context of the present study, Math Fluency is considered to be a partial test of the automatic visual/fact route in that the responses were written. This automatic visual/fact route appeared well developed in the ND group.

In contrast, when the disability groups had to solve basic facts, their answers may not have always been automatically retrieved. For example, if the ND group saw  $2 + 2$ , the visual/fact route might automatically retrieve 4, whereas the RD, MD, and RD+MD children could be employing some level of breaking down the fact and/or using their fingers as visual working memory aids to help retrieve the fact (Geary, 2004). These children may be employing a ‘backup’ strategy (Geary, 2004) to inadvertently reduce working memory load. It cannot be ruled out that the three disability groups may have been adversely affected by some level of written output weaknesses much like a poor reader with weak sight word retrieval (i.e., retrieval of common spelling patterns) also exhibits difficulty with spelling. Deficits in written output were not addressed in this study and would require further investigation.

In screening, the poor mathematicians were defined on the basis of weak Calculation scores, not on Applied Problems or Math Fluency performance. It would be predicted that an RD, MD, and RD+MD group initially defined using Math Fluency measures alone (or a combination of scores on math achievement tests) could have a different profile of math achievement and cognitive strengths and weaknesses. Definitional criteria for the present groups should be taken into consideration when interpreting the results, and generalization of results beyond this sample is not warranted until further data are collected.

### *Automatic Retrieval Profiles for Each Group*

Overall, the good readers and good mathematicians (ND group) showed strong automaticity in the accurate and speedy retrieval of: RAN digits and letters, Benchmark (high frequency) and Exception words, Math Fluency, and math facts (addition, subtraction, and multiplication). The ND group showed solid automaticity for all reading and math tasks. In terms of the single disability groups, the good readers and poor mathematicians (MD group) were just as strong as the ND group on the reading tasks including automatic (i.e., accurate and speedy) retrieval of: RAN letters and digits, and Benchmark (high frequency) and Exception words. Compared to the ND group, the MD group demonstrated unique cognitive processing deficits in their less accurate and slower automatic retrieval of all math facts (easy and difficult addition, subtraction, and multiplication) and Math Fluency.

Compared to all other groups, the RD group was less accurate on RAN letters (a difference of approximately 1 letter). Relative to the good readers (ND and MD groups), the poor readers (RD and RD+MD) showed a deficit in automatic visual/orthographic processing characterized by significantly slower speed of RAN letter and digit retrieval. This finding is consistent with much research on slow naming speed in poor readers (for review, see Bowers & Ishaik, 2003; Wolf & Bowers, 1999) and with research that generally showed that rapid naming of digits is related to math achievement (e.g., RAN digits) (Denckla & Rudel, 1976; Wolf, 1991).

The poor readers (RD and RD+MD) also exhibited weaker automatic visual/orthographic retrieval with less accurate and slower retrieval of Benchmark high frequency and Exception words relative to the good readers (ND and MD). This cross-validates research showing that poor readers are generally slower than average readers when

reading words in isolation (e.g., Ehri & Wilce, 1983) and experience difficulty reading irregular/exception words (Lovett, 1987; Manis & Morrison, 1985; Seidenberg, Bruck, & Backman, 1985).

Planned comparisons and Bonferroni testing confirmed that all disability groups were weak on their automatic visual/fact retrieval as seen in their slower Math Fluency, with the comorbid group being the slowest. Geary (2004) suggested that a deficit in math fact retrieval may be a diagnostic feature of MD, but such a deficit may not always be seen across all operations (e.g., deficit in multiplication retrieval and normal subtraction retrieval). In the Ontario curriculum, facts are taught in the following order: addition, subtraction, multiplication, and division. It is logical to learn facts in this order because multiplication has a root in addition (e.g.,  $4 + 4 + 4 = 12$  and  $3 \times 4 = 12$ ). It is also easier to comprehend division when multiplication facts are known (e.g., ‘2 groups of 3 equals 6’ or  $2 \times 3 = 6$  and ‘2 groups of 3 go into 6’ or  $6/3 = 2$ ). Addition facts and multiplication facts are more easily retrieved through an automatic visual/fact route as they tend to be facts that are more easily ‘drilled’ and memorized. Subtraction requires counting backwards and facility with addition facts; division requires facility with multiplication facts. Both subtraction and division appear to make more demands on working memory processes.

Current results showed that the ND group was more accurate and quicker than the three disability groups on easy and difficult addition facts, easy and difficult subtraction facts, and difficult multiplication facts. The ND group produced more accurate ‘automatic’ (<1sec) easy subtraction, and difficult multiplication, and more accurate ‘working memory processing’ (>1sec) of difficult subtraction facts, and easy and difficult multiplication facts, than all three disability groups. Overall the ND group had a much more efficient automatic

visual/fact store and retrieval rate than all disability groups. They were also more accurate on difficult facts that required more algorithmic and working memory processing.

The good reader/poor mathematicians (MD group) did not show deficits in the automatic visual/orthographic route but they did show weak automatic visual/fact deficits (Math Fluency and all math facts). This is consistent with many studies in which children with MD had significantly weaker automatic retrieval of basic math facts (Bull & Johnston, 1997; Garnett & Fleischner, 1983; Geary, 1993; Geary & Brown, 1991; Geary et al., 1987; Jordan & Montani, 1997; Ostad, 1997). Notably, the automatic visual/fact deficits were specific in this MD group in that the 'automatic visual deficit' did not appear to overlap into an automatic visual/orthographic deficit for word reading.

The current results revealed that the RD group were just as weak in Math Fluency and just as weak in accuracy for specific math facts (e.g., easy multiplication, and difficult subtraction facts requiring working memory processing) as the MD group. This suggests some overlap in visual/orthographic word and visual/fact retrieval for the RD group - beyond having their weakness on the RAN task.

The current study found the comorbid RD+MD group exhibited a weak automatic visual/orthographic route equivalent to that of the RD group, and that they had a much weaker automatic visual/fact route (for easy and difficult addition, difficult subtraction facts, and on Math Fluency) than both of the single disability groups (RD and MD). Similar to the RD group, the comorbid RD+MD group showed deficits in their visual/orthographic route with more severe deficits in their visual/fact deficit routes than both single disability groups. Taken together, these findings suggest that the RD+MD group might have a generally faulty

automatic visual route (e.g., visual/orthographic and visual/fact routes). This speculation requires additional examination and validation through future research.

#### *Working Memory Span Profiles for Each Group*

The good readers (ND and MD) exhibited better developed letter span than the poor readers (RD and RD+MD). The ND group had more digit span capacity than both of the single disability groups, who had similarly weak digit span. It is notable that the poor readers had weak span for both letters and digits. This result is compatible with research showing that poor readers exhibit a reduced working memory span for verbal material (e.g., letters and digits) (Baddeley, 1986; Holligan & Johnston, 1988; Rapala & Brady, 1990). While working memory deficiencies have consistently been shown to be associated with MDs (Geary 1990, 1993, 2004), the present study found that the poor mathematician MD group had weaker digit span and good letter span. The comorbid RD+MD group had similarly weak letter span as the RD poor readers and weaker digit span than both of the single RD and MD groups.

In the present study, the two single disability groups produced significantly more accurate answers to difficult multiplication facts requiring processing/working memory (e.g. total correct in > 1 second) than the RD+MD group. This finding might be attributed to the comorbid group having weaker working memory span than the two single disability groups.

#### *Phonological Processing Profiles for Each Group*

The good readers (ND and MD) had significantly higher Elision and Nonword Repetition performance than the poor readers (RD and RD+MD), with both groups of poor readers showing deficits in phonological processing. In this sample, phonological deficits appear unique to poor readers (RD and RD+MD) and were not observed in the single MD

group. This finding cross-validates research showing that deficits in phonological awareness are found to be a specific and major contributor to reading failure (e.g., Bradley & Bryant, 1983; Fletcher et al., 1994; Mann, 1984; Shankweiler et al., 1995; Siegel, 2003; Stanovich & Siegel, 1994).

#### *Algorithmic Processing Profiles for Each Group*

The good mathematicians' (ND and RD) initial performance on Calculation was superior to the poor mathematicians' (MD and RD+MD) performance. On algorithmic processing measures, the good mathematicians showed significantly better accuracy scores on the addition, subtraction, and multiplication algorithms (i.e., operations) than the poor mathematicians (MD and RD+MD). Thus, algorithmic processing, as defined in this study, appeared to be a unique deficit of poor mathematicians (MD and RD+MD).

In this study, the single MD and comorbid RD+MD poor mathematicians both had weak algorithmic processing on addition algorithms only. The comorbid RD+MD group was weaker than the MD group on subtraction, multiplication, and division algorithms than the single MD group. For this age group, division algorithms are considered a challenge. The ND group met this challenge and was significantly more accurate on the division algorithms than all disability groups. The RD group was relatively more accurate on division algorithms than the poor mathematicians (MD and RD+MD groups).

## PART II

### Procedure

#### *Structural Equation Models (SEMs)*

##### *Apriori Factors/Composites in the Four Factor READ and MATH Models*

Based on the cognitive and functional neurobiological literature on the cognitive processing deficits associated with reading and/or math disabilities, a systems analysis was run using the READ and MATH SEM models. Within each of the READ and MATH systems, it was proposed that the automaticity factor represents common cognitive (and functional neurobiological) processes underlying reading and math acquisition, processes that require the ability to rapidly identify the sound or name associated with visual information (e.g., familiar letters, digits, words, and math facts). When words and facts are unfamiliar, or not automatically identifiable as a whole, more advanced ‘strategy-based processes’ must ‘kick in.’ These advanced processes are represented by the phonological processing (awareness and decoding) factor, the algorithmic (calculation and procedure) processing factor, and the verbal/nonverbal reasoning factor.

Significant intercorrelations between these factors may represent how these four cognitive processes work in partnership. Theoretically, it was proposed that efficient readers and mathematicians increase word reading and math calculation efficiency by first retrieving the part of the word or fact that has been automatically identified. Then they must employ working memory span, utilizing verbal rehearsal and/or visualization to keep the familiar and now unfamiliar parts, ‘online’ in a working order. The more automatically information is identified (e.g., immediately reading a whole word form, or identifying the solution to a math fact), the more capacity the working memory system has for higher processing loads. The

capacity of verbal and visual working memory span places limits on the amount of information the higher order processes can simultaneously keep online to ‘work on.’ Good readers’ and/or good mathematicians’ strong phonological or algorithmic processing, and solid IQ reasoning abilities are proposed to enhance this systems accuracy.

Following this line of reasoning, two four factor models, the READ Model and the MATH Model, were tested. Each model included four factors: 1. Automatic (RAN and words or facts), 2. Working Memory Span (digits and letters), 3. Phonological or Algorithmic Processing, and 4. WASI IQ. Using the entire sample (N = 221), these two models were initially assessed for best fit and, if necessary, other models with more or fewer factors were also assessed to see if they generated a better fit for the current data. Using the best fit models for reading and math, the amount of unique and shared variance for each of the four factors was investigated. The amount of variance contributed by each task to its’ assigned factor (e.g., RAN digits to Automatic) was also established. Raw scores were used for all SEM analyses.

*The Four Factor READ Model (as seen in Figure 20) is itemized as follows:*

1. Automatic/Words - a common underlying cognitive process in reading that allows rapid identification of familiar symbols through an automatic visual/orthographic route includes: letter names (e.g. as in RAN), high frequency Benchmark keywords, and orthographic patterns that cannot be phonetically ‘sounded out’ in their entirety (e.g., Exception words).
2. Phonological Processing – when a whole word can not be read automatically, phonological processing must be employed to break words into familiar and unfamiliar phonemes in order to figure out the whole word. Phonological processing includes: a)

phonological knowledge or awareness (e.g., CTOPP's Elision task) and b) 'phonological' working memory (e.g., Nonword Repetition). Phonological processing employs working memory strategies (e.g., rehearsal and/or visualization) to break down words into appropriate grapheme units, apply the correct phoneme sound(s), and blend the sounds (according to phonological rules).

3. Working Memory Span— online capacity is commonly measured on the WISC-III (now WISC-IV) using the Digit Span task. A structurally similar Letter Span task was also used. To increase accuracy and maximize span length, the working memory system must employ a verbal rehearsal and/or visualization strategy to hold the digits and letters online while they are repeated forwards or backwards. This system is employed by phonological processing and verbal/nonverbal reasoning to hold the familiar and unfamiliar information online in order to figure out the answer.
4. VIQ and PIQ (WASI) – included expressive Vocabulary, Verbal Reasoning (e.g., Similarities), nonverbal reasoning (e.g., Matrix Reasoning), and visual-spatial organization (e.g., Block Design).

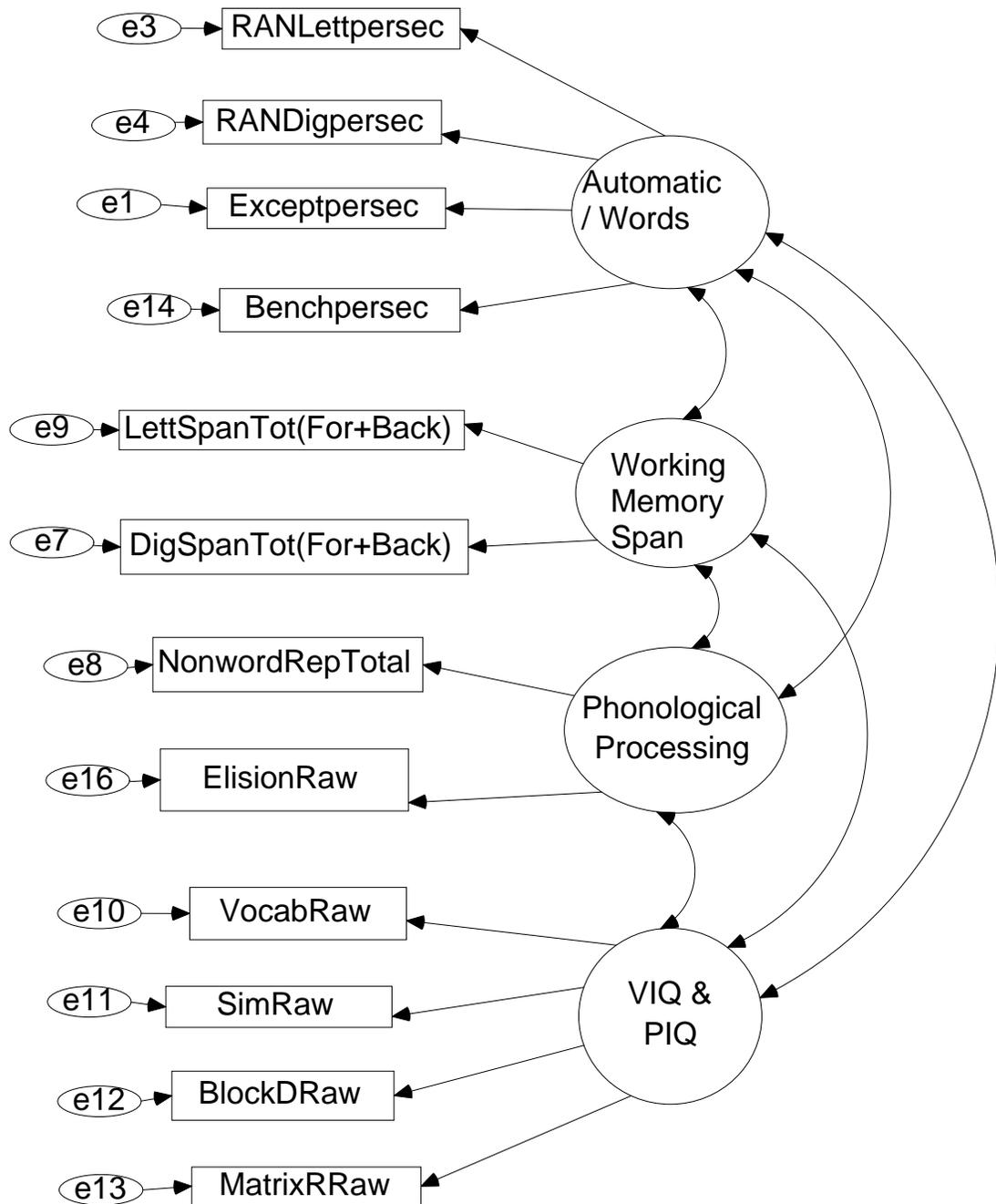


Figure 20. Four Factor READ Model.

*The Four Factor MATH Model (as seen in Figure 21) itemized as follows:*

1. Automatic/Math Facts - a common underlying cognitive process in math that through an automatic visual/fact route allows rapid identification of familiar symbols such as: digit names (as in RAN), and final answers to high frequency math facts (WJ-III Math Fluency), and Evans (2008) Easy and Difficult Math Facts.
2. Algorithmic Processing – when the answer to a math fact or calculation can not be automatically retrieved, algorithmic processing must be employed to break unfamiliar facts or calculations into familiar and unfamiliar parts in order to figure out the answer. Algorithmic processing includes: a) algorithmic or calculation knowledge and b) ‘algorithmic’ working memory (e.g., used in KeyMath Operations ). Both must be employed to break down more difficult facts and calculations into appropriate chunks, and to put them together (according to algorithmic rules) online in working memory – using verbal rehearsal and/or visualization span.
3. Working Memory Span– online capacity is commonly measured on the WISC-III (now WISC-IV) using the Digit Span task. A structurally similar Letter Span task was also used. Working memory span is employed when math facts and calculations are not retrieved automatically and the familiar and unfamiliar must be held online in order to figure out the answer.
4. VIQ and PIQ (WASI) – included Expressive Vocabulary, Verbal Reasoning (e.g., Similarities), Nonverbal reasoning (e.g., Matrix Reasoning), and visual-spatial organization (e.g., Block Design).

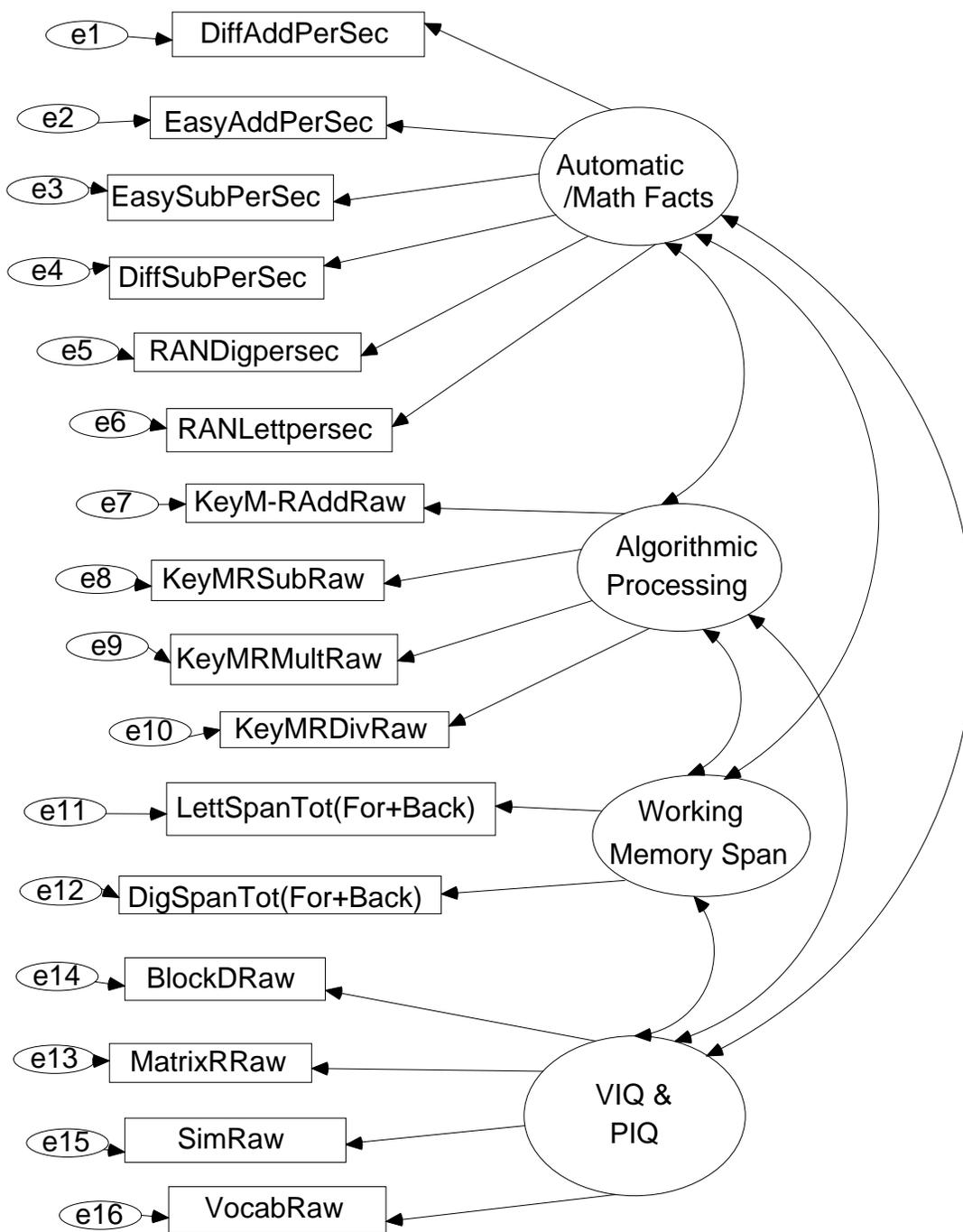


Figure 21. Four Factor MATH Model.

## Results

To test the validity of each model, a maximum likelihood confirmatory factor analysis was performed. Models were assessed for both goodness of fit and parsimony. For each model, the null model was the independent model in which unobserved variables were assumed to be uncorrelated. The null model was estimated by AMOS 6 using the same sample data as the proposed model. The fit of the proposed models was assessed using fit indices to see if they were superior to the null model. To test each model, the following fit indices were assessed: comparative fit index (CFI), Tucker and Lewis' (1973) index of fit (TLI), Browne and Cudeck's (1993) root mean square error of approximation (RMSEA), and PCLOSE. Each fit indices had different criterion to indicate reasonable fit, including: 1) CFI values of greater than approximately .90 indicated reasonably good fit (Hu & Bentler, 1999), 2) TLI value of .80 to 1.00 values close to 1 indicated very good fit; 3) RMSEA value less than  $\leq .05$  suggested close approximate fit relative to the degrees of freedom; between .05 and .08 indicated reasonable error of approximation, and  $\geq .10$  suggested poor fit (Browne & Cudeck, 1993), and 4) a nonsignificant PCLOSE value.

To evaluate the fit of different models, the parsimony indices were evaluated. They adjusted for model complexity (i.e., they prefer simpler models) (Kline, 2005). To assess parsimony, the parsimony-adjusted normed fit-index (PNFI) (James, Mulaik, & Brett, 1982) was used in the present study. To investigate the predictive fit of the data, the Akaike information criteria (AIC) (Anderson, Burnham, & Thompson, 2000) was also assessed. This index investigated hypothetical samples of similar size that were randomly taken from the study's data sample. It also measures parsimony because it prefers less complex models (Kline, 2005). When comparing two models for best fit and parsimony (e.g., the four factor

versus five factor READ or MATH models), the model with the lower AIC typically has the better fit and is more parsimonious (Kline, 2005). The critical difference between two models' chi-squares was also assessed. If the critical difference was significant, the model with the larger degrees of freedom would be considered 'overidentified' in comparison to the model with the lower degrees of freedom (Kline, 2005). Thus, the underidentified model would be accepted to best fit the data (Raykov & Marcoulides, 2000).

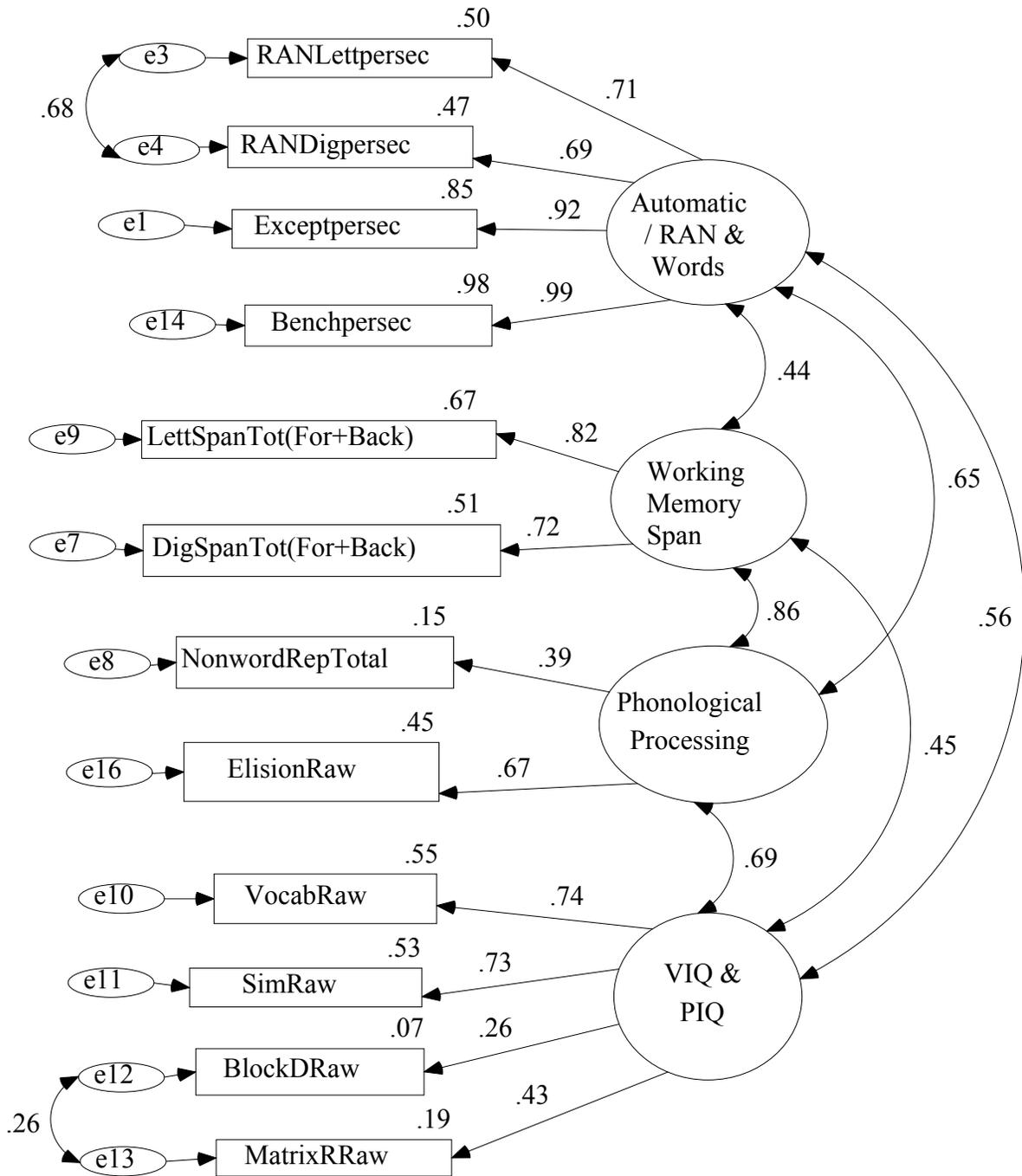
*Confirmation of the READ Model.* A four and five factor READ model are shown in Figures 22 and 23. A four and five factor MATH model are shown in Figure 24 and 25. The factors or composites (e.g., Automatic) are represented by the ovals. The values on the double-headed arrows at the right of the figure show the correlations among the composites. The values on the single-headed arrows from the composites to each of the subtests (represented by rectangles) show the regression weights. The regression weights show the amount of each subtest's variance that is common with the other subtests attached to the same composite. The values on the top right corner of each rectangle/subtest show the squared multiple correlation or the amount of variance that the individual subtest contributes to the factor. The e values in the small ovals at the left of the figure, with a single-headed arrow pointing toward each subtest, are set to one, assuming that the unique and systemic variance for each subtest was equal. According to specified modification indices, to improve the model fit, errors (e.g., e3 and e4, and e12 and e13) are connected using a double-headed arrow. The values on these two arrows show the correlation between the unique and systemic variance of the two subtests (e.g., method variance).

The results of the confirmatory factor analysis demonstrated that the design of the four composites (seen in Figure 22) was supported by the current data (N = 211 and chi-

square = 69.083,  $df=46$ ,  $p=.015$ ). All regression weights, and factor covariances were significant ( $p < .01$ ). The goodness-of-fit indices were good: CFI = .981, TLI = .973, RMSEA = .049, PCLOSE = .506, ns. We can conclude that the subtests were appropriately chosen for each factor/composite and that that composites are valid indicators of 1) Automatic Words, 2) Phonological Processing, 3) Working Memory Span, and 4) WASI VIQ/PIQ.

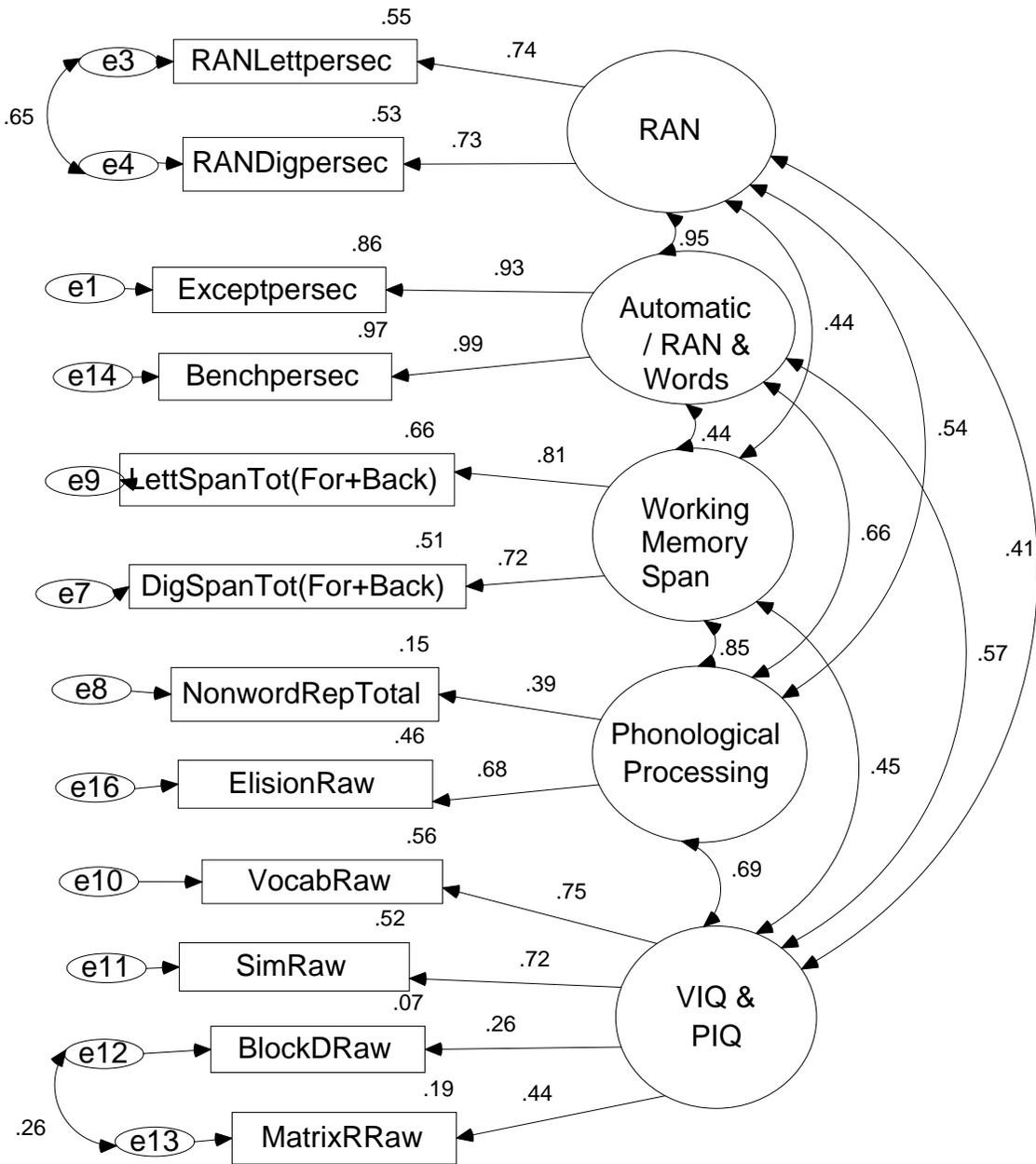
A five factor model (seen in Figure 23), separating RAN from Automatic Words (Benchmark word list and Exception word list per sec.) was also assessed ( $N = 211$  and chi-square = 69.083,  $df=46$ ,  $p=.015$ ). All regression weights, and factor covariances were highly significant ( $p < .01$ ) (chi-square = 69.083,  $df$  (corrected for nonidentifiability) = 43,  $p=.021$ ). All regression weights, and factor covariances were significant ( $p < .01$ ). While the model also had good fit (CFI = .983, TLI = .974, RMSEA = .048, PCLOSE = .524, ns), the critical difference between the four and five factor model Chi-square's were not significant and the correlation between RAN and Automatic Words was highly significant ( $r = .95$ ,  $p < .01$ ). For the four factor model, the parsimony indices were lower: AIC = 157.09, BCC = 162.9, PCFI = .68, PNI = .66 than for the five factor model: AIC = 159.93, BCC = 166.27, PCFI = .64, PNI = .62. With these results and the smaller sample sizes (particularly the RD group), later hierarchical regression analyses were run using the more parsimonious four factor model.

Other nested models were assessed, including: 1) a five factor model, separating VIQ from PIQ, and 2) a three factor model combining Working Memory (Digit & Letter Span) with Phonological Processing. The Four Factor READ Model (combining and separating RAN and Automatic Sight Words) remained the best fit in terms of goodness of fit and parsimony indices.



X<sup>2</sup>=69.093, df=46, p=.015, TLI=.973, CFI=.981, RMSEA=.049, LO90=.022, HI90=.072, PCLOSE=.506, PRatio=.697, PNI=.659, PCFI=.684, AIC=157.093, BCC=162.900

Figure 22. Confirmatory factor analysis of four factor READ model.



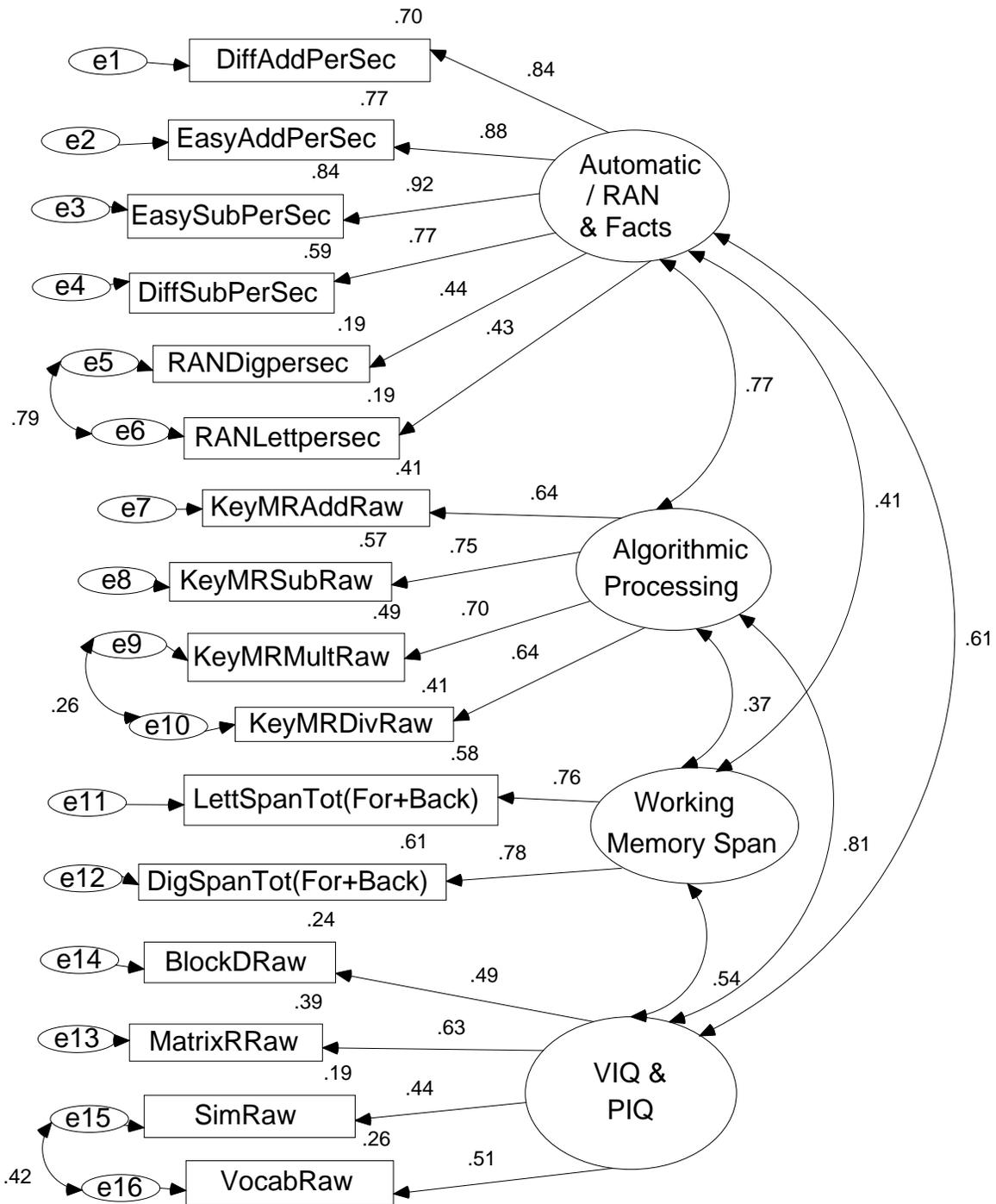
X<sup>2</sup>=63.930, df=43, p=.021, TLI=.974, CFI=.983, RMSEA=.048, LO90=.019, HI90=.072, PCLOSE=.524, PRatio=.652, PNI=.619, PCFI=.640, AIC=159.930, BCC=166.265

Figure 23. Confirmatory factor analysis of five factor READ model.

*Confirmation of the MATH Model.* Results of the factor analysis confirmed that the design of the four composites for the MATH model (as seen in Figure 24) was supported by the current data ( $N = 208$ , chi-square = 146.337,  $df=95$ ,  $p < .01$ ). All regression weights and factor covariances were significant ( $p < .01$ ). The goodness-of-fit indices were good (CFI = .968, TLI = .959, RMSEA = .051, PCLOSE = .439, ns). We can conclude that the subtests were appropriately chosen for each composite and that the composites are valid indicators of Automatic Facts, Algorithm Processing, Working Memory Span, and WASI VIQ/PIQ.

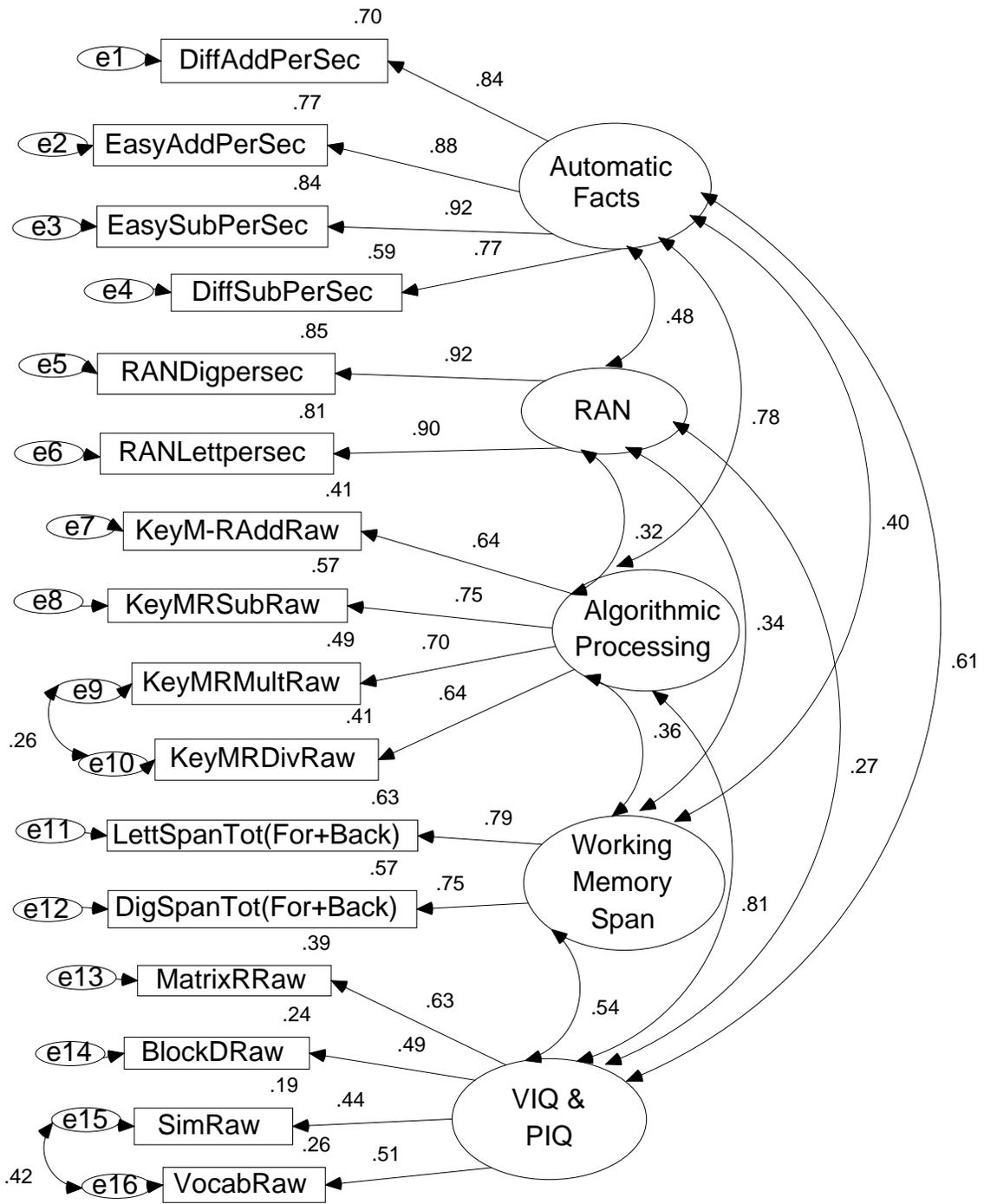
A five factor model, separating RAN from Automatic Facts (Easy and Diff Addition and Subtraction facts per sec.) was also assessed (as seen in Figure 25) ( $N = 208$ , chi-square = 140.741,  $df=92$ ,  $p < .01$ ). All regression weights, and factor covariances were significant ( $p < .01$ ) (note: the correlation between RAN and IQ was significant at  $p = .011$ ). While the five factor model also had good fit (CFI = .969, TLI = .960, RMSEA = .051, PCLOSE = .460, ns), the Chi Square critical difference was not significant and the correlation between RAN and Automatic Words was highly significant ( $r = .48$ ,  $p < .01$ ). For the four factor model, the parsimony indices were quite similar (AIC = 228.34, BCC = 235.67, PCFI = .77, PNI = .72) relative to the five factor model (AIC = 228.74, BCC = 236.61, PCFI = .74 PNI = .70). With these results and the smaller sample sizes (particularly for the RD group), later hierarchical regression analyses were run using the more parsimonious four factor model.

Other nested models were assessed, including: 1) a five factor model, separating VIQ from PIQ, and 2) a three factor model combining Working Memory (Digit & Letter Span) with Algorithm Processing. The Four and Five Factor Math Models (combing and separating RAN and Math Facts) remained the best fit in terms of goodness of fit and parsimony indices.



$X^2=146.337$ ,  $df=95$ ,  $p < .01$ ,  $TLI=.959$ ,  $CFI=.968$ ,  $RMSEA=.051$ ,  $LO90=.034$ ,  $HI90=.067$ ,  $PCLOSE=.439$ ,  $PRatio=.792$ ,  $PNI=.724$ ,  $PCFI=.766$ ,  $AIC=228.337$ ,  $BCC=235.674$

Figure 24. Confirmatory factor analysis for four factor MATH model.



$\chi^2=140.741$ ,  $df=92$ ,  $p < .01$ ,  $TLI=.960$ ,  $CFI=.969$ ,  $RMSEA=.051$ ,  $LO90=.033$ ,  $HI90=.067$ ,  
 $PCLOSE=.460$ ,  $PRatio=.767$ ,  $PNI=.703$ ,  $PCFI=.743$ ,  $AIC=228.741$ ,  $BCC=236.614$

Figure 25. Confirmatory factor analysis for five factor MATH model.

Table 11.

Intercorrelations of Composites of Four Factor READ Model (N = 211)

Composite	Automatic RAN/Words	Working Memory Span	Phonological Processing	VIQ & PIQ
Automatic (RAN/Words)	--	.44**	.65**	.56**
Working Memory Span		--	.85**	.45*
Phonological Processing			--	.69**
VIQ/PIQ				--

\*\* significant at  $p < .01$

Table 12.

Intercorrelations of Composites of Four Factor MATH Model for Entire Sample (N = 221)

Composite	Automatic RAN/Facts	Working Memory Span	Algorithm Processing	VIQ & PIQ
Automatic (RAN/Facts)	--	.41**	.77**	.61**
Working Memory Span		--	.37**	.54**
Algorithmic Processing			--	.81**
VIQ/PIQ				--

\*\* significant at  $p < .01$

## Discussion

The second part of the present study was exploratory, and assessed two Structural Equation Models (SEMs) for the entire sample of participants. Unfortunately, the N in each group was not large enough to run the SEMs separately for each group. The results best support a four factor READ model: 1) Automatic RAN/words (RAN letters, RAN digits, Exception and Benchmark words per sec.), 2) Working Memory Span (Digit and Letter Span), 3) Phonological Processing (Elision and Nonword Repetition), and 4) Verbal/Nonverbal reasoning, with factors representing significantly unique variance and significant intercorrelations with each other. The results also best supported a four factor MATH model: 1) Automatic RAN/math facts (RAN letters, RAN digits, and easy/difficult addition and subtraction facts per sec.), 2) Working Memory Span (Digit and Letter Span), 3) Algorithmic Processing (KeyMath-R Operations: Addition, Subtraction, Multiplication, and Division), and 4) Verbal/Nonverbal reasoning. Within each model, there was a strong representation for each of the underlying cognitive processes proposed. The unique contributions of all of the measures to their specified factor/composite were highly significant, as were the unique and shared variances between the four composites.

Notably, the Working Memory Span and Verbal/Nonverbal reasoning factors used the same measures for both models. Comparing the READ and MATH models, the correlations between Working Memory Span and automatic RAN/Words and automatic RAN/Facts were  $r = .44$  and  $r = .41$ , respectively. The correlation between automatic RAN/Words and Phonological Processing was  $r = .65$ . The correlation between automatic RAN/Facts and Algorithmic Processing was  $r = .77$ . These findings support the hypothesis that Phonological Processing relied on the automatic visual/orthographic retrieval route (e.g.,

automatic RAN/Words), and Algorithmic Processing relied on the automatic visual/fact retrieval route (e.g., automatic RAN/Facts). The correlations between working memory span and phonological processing, and working memory span and algorithmic processing were  $r = .86$  and  $r = .37$ , respectively. This raises the question as to whether working memory span contributes differently to phonological and algorithmic processing. This question requires further investigation.

The findings from the READ and MATH models also support the hypothesis that verbal/nonverbal reasoning works in partnership with automatic visual/orthographic and visual/fact routes, working memory span, and phonological and algorithmic processes. The correlations between verbal/nonverbal reasoning and automatic RAN/ Words and RAN/Facts were  $r = .56$  and  $r = .61$ , respectively. The correlations between working memory span and verbal/nonverbal reasoning were  $r = .45$  and  $r = .54$ , respectively. The correlations between verbal/nonverbal reasoning and phonological processing and algorithmic processing were  $r = .69$  and  $r = .81$ . Whether cognitive processes, such as verbal/nonverbal reasoning, contribute differently to phonological and algorithmic processing requires further investigation.

The four factor READ and MATH SEM models were validated, showing best fit and significant unique (i.e., significant latent variables) and significant shared variance (i.e., intercorrelations in Table 11 and 12). These findings support the proposed READ and MATH system framework; the theoretically-derived automatic processing, working memory, and verbal/nonverbal fluid reasoning factors within the READ and MATH systems work uniquely and in collaboration. It is proposed that this significant collaboration among all partners/factors involves an attempt of the system to increase the storage capacity, accuracy, fluency, and overall efficiency of the system.

## PART III

### Procedure

#### *Predicting Achievement with the READ and MATH Factors for Each Group*

For each of the four groups, each of the WJ-III achievement tests (LWID, WA, Calculation, Applied Problems, and Math Fluency) were used as predicted variables and the four composites from the Reading and then the Math structural equation models were entered separately into stepwise regression equations (e.g., with LWID as the predictor variable for the READ model composites:  $LWID = \text{Automatic RAN/ Words} + \text{Phonological Processing} + \text{Working Memory Span} + \text{WASI IQ}$ ; and using the MATH model composites:  $LWID = \text{Automatic RAN/ Facts} + \text{Algorithmic Processing} + \text{Working Memory Span} + \text{WASI IQ}$ ). This method was designed to test the main hypothesis that the underlying cognitive processes of automatic (RAN/ and words or facts), phonological or algorithmic processing, working memory span and IQ are employed, both uniquely and in partnership, to read words and solve math calculations that are familiar and those that are unfamiliar. Thus, one or more of the READ model or MATH model cognitive process/composite(s) was anticipated to predict a significant amount of variance in each of the WJ-III reading and math predictor variables. It was anticipated that the amount of variance accounted for by each composite (i.e., cognitive process) would vary in its predictability, depending on each group's achievement (i.e., ceiling level) on the WJ-III test that was being predicted, and depending on each group's cognitive strengths and weaknesses.

### Results

Results of the regression analyses for each achievement test are shown below.

Table 13.

Stepwise Multiple Regression Analyses Predicting Letter Word Identification (LWID) using the Four Latent Measures from the READ and MATH Structural Equation Models (SEM)

SEM	Group	Model	R <sup>2</sup>	R <sup>2</sup> Change	F	p	df
READ	ND N=71	1: Automatic	.32	.32	33.05	.000	1,70
		(RAN/Words)					
		2: WASI VIQ/PIQ	.39	.07	22.40	.000	2,69
RD	N=35	1: Automatic	.58	.58	46.67	.000	1,34
		(RAN/Words)					
MD	N=64	1: Phonological Processing	.40	.40	41.79	.000	1,63
		(RAN/Words)					
		2: Automatic	.44	.04	24.36	.000	2,62
		(RAN/Words)					
RD+MD	N=49	1: Automatic	.67	.67	95.67	.000	1,48
		(RAN/Words)					
		2: Phonological Processing	.76	.09	73.28	.000	2,47
MATH	ND N=71	1: Algorithmic Processing	.39	.39	45.45	.000	1,70
		(RAN/Words)					
	RD N=35	-----					1,34
MD	N=64	1: Working Memory	.18	.18	13.51	.000	1,63
		Span					
RD+MD	N=49	1: Automatic (RAN/Facts)	.52	.52	51.52	.000	1,48
		2: Working Memory Span	.56	.04	29.96	.000	2,47

*READ model predicting LWID.* As seen in Table 13, within the ND group the Automatic composite accounted for 32% of the variance when predicting LWID with the WASI VIQ/PIQ accounting for 7% more for a total of 39%. For the RD group, the Automatic composite accounted for 58% of the variance when predicting LWID performance. For the MD group, the Phonological Processing Composite accounted for 40% of the variance when predicting LWID with the Automatic composite accounting for another 4% for a total of 44%. For the RD+MD group, the Automatic composite accounted for 67% of the variance of LWID, with the Working Memory composite contributing 9% more, for a total of 76%.

*MATH model predicting LWID.* As seen in Table 13, within the ND group, the Algorithmic Processing composite accounted for 39% of the variance when predicting LWID. For the RD group, none of the four math composites (Automatic, Algorithmic Processing, Working Memory, or WASI) predicted LWID. For the MD group, the Working Memory Composite accounted for 18% of the variance when predicting LWID. For the RD+MD group, the Automatic composite accounted for 52% of the variance of LWID, with the Working Memory composite contributing 4% more, for a total of 56%.

Table 14.

Stepwise Multiple Regression Analyses for Word Attack using the Four Latent Measures  
from the READ and MATH Structural Equation Models (SEM)

SEM	Group	Model	R <sup>2</sup>	R <sup>2</sup> Change	F	p	df
READ	ND	1: Phonological Processing	.23	.23	20.47	.000	1,70
	N=71						
	RD	1: Automatic	.31	.31	14.95	.000	1,34
	N=35	(RAN & Words)					
READ	MD	1: Automatic	.33	.33	31.22	.000	1,63
	N=64	(RAN & Words)					
	RD+MD	1: Phonological Processing	.52	.52	52.39	.000	1,48
	N=49						
MATH	ND	1: WASI VIQ/PIQ	.13	.13	10.35	.002	1,70
	N=71						
	RD	1: Algorithmic Processing	.11	.11	4.33	.05	1,34
	N=35						
MATH	MD	1: Automatic (RAN & Facts)	.19	.19	14.45	.000	1,63
	N=64						
	RD+MD	1: Working Memory Span	.32	.32	22.57	.000	1,48
	N=49	(Digit & Letter Span)					

*READ model Predicting WA.* As seen in Table 14, within the ND group, the Phonological Processing composite accounted for 23% of the variance when predicting WA. For the RD group, the Automatic/Words composite accounted for 31% of the variance when predicting WA performance. For the MD group, the Automatic Composite accounted for 33% of the variances when predicting WA. For the RD+MD, the Phonological Processing composite accounted for 52% of the variance when predicting WA.

*MATH model predicting WA.* As seen in Table 14, within the ND group, the WASI VIQ/PIQ composite accounted for 13% of the variance when predicting WA. For the RD group, the Algorithmic Processing accounted for 11% of the variance when predicting WA. For the MD group, the Automatic composite accounted for 19% of the variance when predicting WA. For the RD+MD group, the Working Memory composite accounted for 32% of the variance when predicting WA.

Table 15.

Stepwise Multiple Regression Analyses for Math Fluency using the Four Latent Measures from the READ and MATH Structural Equation Models (SEM)

Model	Group	Model	R <sup>2</sup>	R <sup>2</sup> Change	F	p	df
READ	ND	1: Automatic (RAN/Words)	.37	.37	41.51	.000	1,70
	N=71						
	RD	1: Automatic (RAN/Words)	.44	.44	27.21	.000	1,34
	N=35						
	MD	1: Automatic (RAN/Words)	.37	.37	36.98	.000	1,63
	N=64						
	RD+MD	1: Automatic (RAN/Words)	.50	.50	48.22	.000	1,48
	N=49	2: Phonological Processing	.57	.07	31.59	.000	2,47
MATH	ND	1: Automatic (RAN/Facts)	.66	.66	138.35	.000	1,70
	N=71						
	RD	1: Automatic (RAN/Facts)	.47	.47	30.27	.000	1,34
	N=35	2: Working Memory					
		(Digit & Letter Span)	.55	.08	5.8	.000	2,33
	MD	1: Automatic (RAN/Facts)	.56	.56	78.86	.000	1,63
	N=64						
	RD+MD	1: Automatic (RAN/Facts)	.83	.83	239.05	.000	1,48
	N=49						

*READ model predicting Math Fluency.* As seen in Table 15, within the ND group, the Automatic (RAN/words) composite accounted for 37% of the variance when predicting Math Fluency. For the RD group, the Automatic (RAN/words) composite accounted for 44% of the variance when predicting Math Fluency. For the MD group, the Automatic (RAN/words) composite accounted for 37% of the variance when predicting Math Fluency. For the RD+MD, the Automatic (RAN/words) composite accounted for 50% of the variance, and Phonological Processing accounted for an additional 7% of the variance when predicting Math Fluency.

*MATH model predicting Math Fluency.* As seen in Table 15, within the ND group, the Automatic (RAN/facts) composite accounted for 66% of the variance when predicting Math Fluency. For the RD group, the Automatic (RAN/facts) composite accounted for 47% of the variance, with Working Memory accounting for an additional 8%; for a total of 55% when predicting Math Fluency. For the MD group, the Automatic (RAN/facts) composite accounted for 56% of the variance when predicting Math Fluency. For the RD+MD group, the Automatic (RAN/facts) composite accounted for 83% of the variance when predicting Math Fluency.

Table 16.

Stepwise Multiple Regression Analyses for Calculation using the Four Latent Measures from the  
 READ and MATH Structural Equation Models (SEM)

SEM	Group	Model	R <sup>2</sup>	R <sup>2</sup> Change	F	p	df
READ	ND	1: WASI VIQ/PIQ	.30	.30	30.62	.000	1,70
	N=71	2: Automatic					
		(RAN & Words)	.37	.07	20.39	.000	2,69
	RD N=35	-----				.000	1,34
	MD	1: WASI VIQ/PIQ	.18	.18	13.80	.000	1,63
MATH	N=64						
	RD+MD	1: WASI VIQ/PIQ	.27	.27	17.63	.000	1,48
	N=49	2: Automatic	.35	.08	12.28	.000	2,47
		(RAN & Words)					
ND	1: Algorithmic Processing	.61	.61	107.08	.000	1,70	
MATH	N=71						
	RD N=35	1: Algorithmic Processing	.60	.60	50.19	.000	1,34
	MD N=64	1: WASI VIQ/PIQ	.22	.22	17.65	.000	1,63
	RD+MD	1: Algorithmic Processing	.58	.58	67.42	.000	1,48
N=49	2: WASI VIQ/PIQ	.64	.07	43.89	.000	2,47	
	3: Automatic	.68	.04	34.44	.000	3,46	
	(RAN & Facts)						

*READ model predicting Calculation.* As seen in Table 16, within the ND group, the WASI VIQ/PIQ composite accounted for 30% of the variance with the Automatic composite accounting for a further 7% for a total of 37% when predicting Calculation. For the RD group, none of the 4 READ composites predicted the RD groups' scores on Calculation. For the MD group, the WASI VIQ/PIQ composite accounted for 18% of the variance when predicting Calculation. For the RD+MD group, the WASI VIQ/PIQ composite accounted for 27% of the variance, with another 8% being accounted for by the Automatic composite, for a total of 35% when predicting Calculation.

*MATH model predicting Calculation.* As seen in Table 16, within the ND group, the Algorithmic Processing composite accounted for 61% of the variance when predicting Calculation. For the RD group, the Algorithmic Processing accounted for 60% of the variance when predicting Calculation. For the MD group, the WASI VIQ/PIQ composite accounted for 22% of the variance when predicting Calculation. For the RD+MD group, the Algorithmic Processing composite accounted for 58% of the variance, with the WASI VIQ/PIQ composite predicting an additional 7%, and Automatic a final 4%, for a total of 68% of the variance.

Table 17.

Stepwise Multiple Regression Analyses for Applied Problems using the Four Latent Measures from the READ and MATH Structural Equation Models (SEM)

SEM	Group	Model	R <sup>2</sup>	R <sup>2</sup> Change	F	p	df
READ	ND	1: WASI VIQ/PIQ	.34	.34	36.17	.000	1,70
							N=71
	RD	1: WASI VIQ/PIQ	.22	.22	9.30	.000	1,34
							N=35
	MD	1: WASI VIQ/PIQ	.43	.43	46.77	.000	1,63
						N=64	
MATH	ND	1: WASI VIQ/PIQ	.65	.65	130.62	.000	1,70
							N=71
		2: Algorithmic Processing	.68	.03	72.38	.000	2,69
	RD	1: Algorithm Processing	.34	.34	17.25	.000	1,34
							N=35
	MD	1: WASI VIQ/PIQ	.45	.45	52.35	.000	1,63
						N=64	
MATH	RD+MD	1: WASI VIQ/PIQ	.69	.69	108.09	.000	1,48
							N=49
		2: Automatic (RAN & Facts)	.74	.05	66.19	.000	2,47

*READ model predicting Applied Problems.* As seen in Table 17, within the ND group, the WASI VIQ/PIQ composite accounted for 34% of the variance when predicting Applied Problems. For the RD group, the WASI VIQ/PIQ composite accounted for 22% of the variance when predicting Applied Problems. For the MD group, the WASI VIQ/PIQ Composite accounted for 43% of the variance when predicting Applied Problems. For the RD+MD group, the WASI VIQ/PIQ composite accounted for 55% of the variance, with another 7% being accounted for by the Automatic composite, for a total of 63% when predicting Applied Problems.

*MATH model predicting Applied Problems.* As seen in Table 17, for the ND group, the WASI VIQ/PIQ composite accounted for 65% of the variance when predicting Applied Problems, with the Algorithmic Processing composite accounting for an additional 3%, for a total of 68%. For the RD group, the Algorithmic Processing composite accounted for 34% of the variance when predicting Applied Problems. For the MD group, the WASI VIQ/PIQ composite accounted for 45% of the variance when predicting Applied Problems. For the RD+MD group, the WASI VIQ/PIQ composite accounted for 69% of the variance, with the Automatic composite predicting an additional 5%, for a total of 74% of the variance accounted for.

## Discussion

In the third part of the present research, it was hoped that each achievement task could be drawn on the right of each SEM model as a predictor variable, with arrows coming from each composite, in order to measure the unique and shared variance that the composites in each of the READ and MATH models contributed when predicting each of the two reading achievement tasks (e.g., LWID and WA) and each of the three math achievement

tasks (e.g., Math Fluency, Calculation, and Applied Problems). However, due to the relatively small sample size of each group this type of analysis could not be pursued.

Instead regression equations were designed to investigate the underlying cognitive processes, represented by the composites in the READ and MATH models that best predicted the performance of the groups on each of the reading and math achievement measures. By using regression analysis instead of SEM analysis, the contributing covariance of the four factors in each of the READ and MATH models, when predicting reading and math achievement, was sacrificed. However, it was anticipated that by using a stepwise regression approach, that the main cognitive processes (i.e., predictor(s)) that significantly comprised each regression equation could be explained by both the different reading and math achievement levels and the cognitive strength and weakness profiles of each group. This would offer important information about what cognitive processes/routes were being employed by students with ND, RD, MD or RD+MD on the reading and math achievement tests.

It is acknowledged that there was variance in each regression equation that was unaccounted for by the current four READ and MATH model factors. This caveat applies to all groups, but especially the RD group which had the lowest number of participants in this study (N = 36).

#### *Predicting Reading Achievement (LWID and WA)*

*Good readers (ND and MD Groups).* Based on the regression equations run for LWID and WA, using the four factor READ composites, the ND group appeared to rely on their solidly accurate and fast automatic visual/orthographic route (32%) and verbal/nonverbal reasoning (7%) to read words on LWID. These data provide further

support for the ND group's efficient automatic visual/orthographic route. They also employed solid phonological processing accuracy (23%) to decode nonwords on WA. Using the MATH factors, for the ND group, automatic RAN/Facts did not predict LWID, rather, the more advanced/challenging cognitive process, algorithmic processing accuracy (39%), predicted the main variance in LWID and none of the variance in WA. Verbal/nonverbal reasoning (13%) however, predicted decoding nonwords on WA for this 'good-at everything' group.

These findings suggest that the ND group tapped a more advanced store of automatic visual/orthographic information to achieve superior scores on LWID to the poor readers (RD and RD+MD). The MATH factors, automatic RAN/Facts or algorithmic processing, did not predict WA, but phonological processing did when the READ factors were used. This suggests that accurate phonological processing strategies are imperative for good decoding and that it is also a unique process specific to reading—a process that may require higher order verbal/nonverbal reasoning particularly to decode more complex nonwords.

*MD group.* Relative to the ND group, the MD group included similarly good readers with age-appropriate automatic visual/orthographic retrieval and phonological processing. However, MD children were weaker than the ND group in their working memory span for digits, Math Fluency, automatic visual/fact retrieval (for all facts), and they had less accurate algorithmic processing. Thus, contributing factors in the prediction of reading were anticipated to be somewhat different in composition compared to the 'good-at-everything' good readers (ND group).

For words in LWID, the MD good reader group relied on accurate phonological processing (40%) and then automatic RAN/Words (4%); an opposite pattern to the ND

group. Unlike the ND good readers, the MD group did not appear to use automatic visual/orthographic retrieval and instead had to decode these regular words to read as well as the ND group. This pattern might imply some taxation of working memory span for the MD good readers. Compared to the ND good readers, verbal/nonverbal reasoning was not entered when predicting LWID. Again unlike the ND group, the MD good readers relied on automatic RAN/Words (33%) for decoding nonwords on WA; to the ND group appeared to rely more on phonological processing accuracy. This suggests that the two good reader groups (ND and MD) relied on different stores and access routes to reach relatively similar scores on LWID and WA.

Using the MATH factors to predict LWID, working memory (18%) was the main predictive variable for the MD good readers, again suggesting that LWID was not an entirely automatic task for the MD group and required more effortful processing than for the ND group who relied more on accurate processing (i.e., algorithmic processing). When using the MATH factors to predict WA, automatic RAN/Facts (19%) predicted WA. Evidence of access to the automatic visual/orthographic and visual/fact routes for decoding, suggests that it may not be as 'clean' a process as it was for the ND good readers.

*Poor readers (RD and RD+MD groups).* When interpreting the regression equations, it is important to recall the achievement and cognitive profile of the RD group. The RD group was weaker than the good reader groups (ND and MD) in their automatic visual/orthographic route (e.g., less automatic RAN letter accuracy and RAN letter and digit naming speed, less automatic Benchmark and Exception word retrieval), visual/fact route (for more advanced multiplication facts), phonological processing, and working memory span for letters and digits. Compared to the MD group, they had similarly weak Math

Fluency, better math fact retrieval (for addition and subtraction facts), and better algorithmic processing.

When predicting their poor performance on LWID using factors from the READ model, their much weaker visual/orthographic automaticity (i.e., accuracy and speed) for RAN/ Words predicted 58% of the variance of LWID. This finding suggests that compared to the good readers, the RD poor readers relied on a limited automatic visual/orthographic route to read words on LWID. They may not have applied much, if any, phonological processing compared to the good reader groups (ND and MD). Notably none of the MATH factors predicted LWID for this group. The RD group had a very weak visual/orthographic route with weak RAN and automatic word retrieval. In contrast, they had a better established visual/fact route for addition and subtraction facts (which made up the Automatic RAN/Facts composite) with weaker RAN - both in the Automatic RAN/Facts composite. Generally the automatic visual/orthographic route appeared to be weaker than the automatic visual/facts route for the RD poor readers. This maybe why the Automatic RAN/Facts did not predict weaker word reading and/or that automatic visual/orthographic words and visual/facts might be stored and/or accessed from separate sites for the RD group.

While the RD and ND groups did not have significantly different algorithmic processing, both showing age-appropriate performance, the accurate algorithmic processing composite predicted the better LWID performance of the ND group, and it did not predict the poorer LWID performance of the RD group. The ND group was much more accurate than the RD group on this test. When predicting WA, the main predictor for the RD group was their less automatic RAN/Words (31%), further supporting speculation that the RD children employed a weaker automatic visual/orthographic route to decode nonwords, the RD group

did not employ more advanced phonological processing like the MD good readers or higher order reasoning like the ND good readers.

For the RD group, the algorithmic processing accuracy factor accounted for significant but relatively less variance (11%) when predicting WA. This would suggest some level of processing for the RD group when decoding. Again, it must be acknowledged that the RD group had fewer participants; with more RD children, a different or similar pattern, with smaller or larger variance accounted for, may have been found.

*RD+MD group.* The RD+MD group were ‘weak- at- everything’ readers, with an amalgamation of RD and MD deficits. Their extremely slow and limited automatic RAN/Words accounted for 67% of the variance of LWID, with their weaker working memory contributing 9% more, for a total of 76% of the variance accounted for. The RD+MD group had a very weak automatic visual/orthographic route from which to retrieve words. Working memory span also entered into the regression equation for the comorbid RD+MD group, suggesting that they required working memory span to read unfamiliar words possibly to break apart words and hold them online. Compared to the ND and MD good readers, they did not appear to employ higher order reasoning or phonological processing. Compared to the RD group, the automatic visual/orthographic route of the RD+MD group appeared to be more severely compromised in that they relied upon working memory span to hold word parts for words and nonwords online.

When the MATH factors were entered, very weak automatic RAN/Facts (52%) and working memory span (4%) predicted LWID for the comorbid RD+MD group. For the RD weak readers, none of the MATH factors predicted their poorer LWID, although they did rely on their weaker working memory span to read unfamiliar words. The RD+MD group had

severely compromised automatic visual/orthographic and visual/fact routes. This might explain why automatic RAN/Facts predicted LWID for them. There may be overlap (possibly functional neurobiological) in their weaker automatic visual/orthographic and visual/fact retrieval routes for RAN, sight words, and math fact stores, a possibility that requires further exploration.

For WA, the RD+MD group tapped their deficient phonological processing skills (52%) when attempting to decode nonwords, and not their weaker automatic visual/orthographic route as the RD poor readers did. This suggests that this was a more labor-intensive task for them. Similarly, when the MATH factors were used to predict WA, their limited working memory span (32%) was tapped, suggesting that they were attempting to hold parts of basic nonwords online – nonwords that the better readers could retrieve very easily through an automatic visual/orthographic route (ND group) or by employing more advanced phonological processing (MD group).

#### *Predicting Math Fluency*

It is important to acknowledge that Math Fluency is a very basic single digit addition, subtraction, and multiplication (depending on the ceiling) time-limited task that allows the use of paper and pencil. It should also be noted that math facts (easy and difficult addition and subtraction per sec.) made up part of the automatic RAN/fact factor in the MATH model.

*Good readers (ND and MD groups).* For the ND group, using the four READ factors, automatic RAN/Words (37%) predicted Math Fluency. Using the four MATH factors, automatic RAN/Facts (66%) predicted Math Fluency. For the MD group, using the READ factors, automatic RAN/Words factor (37%) was the main predictor of Math Fluency. Using the MATH factors, automaticity RAN/Facts (57%) was the main predictor. It is speculated

that an overlap in RAN/Words and RAN/Facts, or the automatic visual/orthographic and visual/fact routes may be similar for the good readers for very basic, solidly automatic, visual information (e.g., RAN, single digit math facts, and familiar words).

*Poor readers (RD and RD+MD groups).* For the RD group, using the READ factors, automatic RAN/Words (44%) predicted Math Fluency. Using the four MATH factors, automatic RAN/Facts (47%) and working memory span (8%) predicted Math Fluency. For the RD+MD group, using the READ factors, automatic RAN/Words (50%) predicted Math Fluency. Using the MATH factors, the automatic RAN/Facts (83%) predicted Math Fluency. For the poor readers, it is proposed that there may be substantial overlap in RAN/Words and RAN/Facts, or the weak automatic visual/orthographic and relatively weaker visual/fact routes. For the poor readers, especially the comorbid RD+MD group, very basic visual information (e.g., RAN, some single digit math facts, and unfamiliar words) appears to be faulty.

#### *Predicting Calculation*

*Good mathematicians (ND and RD group).* For the ND group, using the READ factors, solid Verbal/Nonverbal reasoning (30%) and highly Automatic RAN/Words (7%) predicted Calculation. Using the MATH factors, highly accurate Algorithmic Processing (61%) predicted Calculation. For the RD group, none of the READ composites predicted the RD group's score on Calculation; the Verbal/Nonverbal reasoning factor did not enter the regression equation. Earlier, when reading achievement was predicted, the ND group also applied Verbal/Nonverbal Reasoning to read words in contrast to the RD group. Using the MATH factors, Algorithmic Processing (60%) was the main unique predictor, suggesting

that good mathematicians relied on this accurate process, regardless of their reading achievement.

*Poor mathematicians (MD and RD+MD group).* For the MD group, using the READ factors, Verbal/Nonverbal reasoning (18%) was the main predictor of Calculation skill – suggesting that automatic visual/orthographic and phonological processes may not have been employed systematically by this group. Using the MATH factors, Verbal/Nonverbal reasoning (22%) was the main significant predictor again. It is notable that Algorithmic Processing, a process for which this group was very weak, was not a predictor as it was for the good mathematicians (ND and RD groups). For the comorbid RD+MD group, using the READ factors Verbal/Nonverbal reasoning (27%) was also a main predictor of Calculation, along with weak Automatic RAN/Words (8%). Of the four groups, the RD+MD group's Verbal/Nonverbal reasoning was relatively lower, their RAN was slower than the ND and MD groups, and their math facts were the weakest. Using the MATH factors, weak Algorithmic Processing (58%), Verbal/Nonverbal reasoning (7%) and weak Automatic (RAN/Facts) (4%) were the significant predictors, all processes on which the RD+MD group were inferior to the ND, RD, and MD groups.

#### *Predicting Applied Problems*

*Good mathematicians (ND and RD group).* For the ND group, using the READ model, Verbal/Nonverbal reasoning (34%) predicted Applied Problems, similar to Calculation. Using the MATH factors, the Verbal/Nonverbal reasoning composite (65%), and Algorithmic Processing composite (3%), predicted Applied Problems. For the RD group, using the READ factors, Verbal/Nonverbal reasoning (22%) predicted Applied

Problems. Using the MATH factors, Algorithmic Processing (34%) predicted Applied Problems, similar to Calculation.

*Poor mathematicians (MD and RD+MD group).* For the MD group, using the READ factors, Verbal/Nonverbal reasoning (43%) predicted Applied Problems. Using the MATH factors, Verbal/Nonverbal reasoning (45%) again predicted Applied Problems. Similar to Calculation, Algorithmic Processing (on which this group performed below age level) did not predict Applied Problems as it did for the good mathematicians. For the comorbid RD+MD, using the READ factors, relatively weaker Verbal/Nonverbal reasoning (55%) and weaker Automatic RAN/Words (8%) predicted Applied Problems. Using the MATH factors, relatively weaker Verbal/Nonverbal reasoning (69%) and significantly weaker Automatic RAN/Facts (5%) predicted Applied Problems. This group had the most compromised automatic visual/orthographic route, working memory, and phonological and algorithmic processing. They also performed at the lowest levels on this Applied Problems task.

## GENERAL DISCUSSION

### Part 1

#### *Group Profiles*

The first part of this study assessed the specific areas of cognitive strength and weakness that are associated with good reading and math skills (ND), single reading (RD) and math disabilities (MD), and comorbid reading and math disabilities (RD+MD). Each group exhibited unique performance profiles across measures representing automatic visual/orthographic and visual/fact routes, working memory span, phonological and algorithmic processing, and IQ or nonverbal/verbal reasoning factors. These cognitive profiles enhanced our understanding of the cognitive strength and weakness patterns associated with good reading and math achievement, single reading or math disabilities, and comorbid learning disabilities.

*Good reader and good mathematician profiles (ND Group).* Overall, the good readers and mathematicians showed solid performance on all tasks, suggesting intact automatic visual/orthographic and automatic visual/fact retrieval routes, solid working memory span capacity, phonological and algorithmic processing accuracy, and solid verbal/nonverbal reasoning. This group's solid performance across all tasks allowed profiling of the single and comorbid disability groups and provided a reference for statistical comparison of cognitive strengths and weaknesses.

*Single disability group profiles (RD and MD groups).* In terms of their automatic visual routes, the single disability groups showed unique deficits, in comparison to each other and relative to the comorbid group. The single RD group demonstrated deficits in their automatic visual/orthographic retrieval, Math Fluency, and in their easy multiplication facts

and difficult subtraction facts requiring working memory processing. The single MD group showed solid visual/orthographic retrieval with a significant deficit in their Math Fluency, and automatic visual/fact retrieval for all operations. The automatic visual/orthographic route deficit appeared unique to the RD group and the severity of the automatic visual/fact route deficit was unique to the MD group; the MD children showed weaker automaticity across all math facts. Notably, the RD group showed some overlap in their automatic visual route retrieval; they had weaker Math Fluency and weaker aspects of the visual/fact route as well.

In terms of working memory span, the RD group's working memory span was just as weak as the MD group's for digit span; however, their letter span was weaker than the ND and the MD group (who had similarly good letter span). Again, the single MD group's automatic retrieval deficit appeared unique to digits, whereas the RD group's overlapped with weaknesses demonstrated on RAN letters and digits and working memory span for letters and digits. There appeared to be a more specific profile of processing deficit in that the RD group showed poor phonological processing with good algorithmic processing, while the MD group exhibited good phonological processing and poor algorithmic processing. The two single disability groups showed similarly average verbal and nonverbal reasoning abilities.

*Comorbid learning disability group profile (RD+MD group).* Assessing the severity of deficits in the comorbid RD+MD group was also a main focus of this study. This group had a similarly weak automatic visual/orthographic route to the single RD group, and a significantly weaker visual/fact route than the single MD group. The comorbid group had weaker working memory span (for letters and digits) than the single disability groups. They

showed similarly weak phonological processing to the RD group, with weaker algorithmic processing (for subtraction, multiplication, and division) than the MD group. They appeared to demonstrate a more severe general deficit in visual route retrieval; their automatic visual/orthographic route was just as weak as the RD group, and their automatic visual/fact route was more severely compromised than the MD groups.

Overall, the RD+MD cognitive profile suggests that more severe deficits in the visual route and working memory system further impact their ability to store and automatically retrieve familiar word and fact information and hold it in working memory. Weaker phonological and algorithmic processing further impedes the comorbid group's word reading and solving of calculations. Although the RD group had broader deficits than the MD group that overlapped into the math domain (e.g., RAN digits, working memory span for digits, visual/fact difficulties for subtraction and multiplication, and poor Math Fluency), the comorbid group had the broadest deficits and were the most disabled across all underlying cognitive processes related to reading and math achievement.

#### *Clinical Application and Future fMRI Research using Group Profiles*

Fuchs et. al. (2006b) suggested more research into the nature of the academic and cognitive correlates areas of different math skill (e.g., ND, MD, and RD+MD). This study addressed this issue by specifying the type of learning disability (MD versus RD+MD) and the achievement test used to identify the groups (e.g., Calculation); allowing for future cross-validation studies. While generalization of these results to clinical issues requires appropriate caution, this type of cognitive profiling could provide psychologists with a functional analysis of cognitive strength and weakness, and information about potential overlap of cognitive processing deficits in single and comorbid reading and math disabilities.

Areas of need can then be better defined and targeted for special educational programming; skills can be observed, measured, and potentially linked to improvements in curriculum-based achievement.

fMRI research could be pursued in the future to investigate the potential separation or overlap of functional neurobiological systems subserving reading and math development. For example, the angular gyrus has been associated with integrating automatic word and phonological processing (Fletcher, Simos, Papanicolaou, and Denton, 2004). Does it also assist with retrieving automatic math facts (DeHaene et al., 1999; Stanesco-Cosson et al., 2000) and integrating algorithmic/calculation processing?

Given the apparent genetic overlap in linkage findings for reading and math disabilities (Kovas, Harlaar, Petrill, & Plomin, 2005) and potential for cognitive and functional neurobiological profiling, early at-risk assessment tools and early intervention strategies might also be developed to improve outcomes for children with these learning disorders.

## Part II

### *Structural equation READ and MATH models*

The good and poor readers and/or mathematicians were characterized across a range of cognitive measures that clustered into theoretically-derived a priori factors. Within each of the READ and MATH SEM models, two of the four factors in each model were Working Memory Span (e.g., Letters and Digits Total) and Verbal/Nonverbal Reasoning (e.g., Vocabulary, Similarities, Block Design, and Matrix Reasoning). A third Automatic factor (i.e., accuracy and fluency) was placed in each model and it was representative of a visual/orthographic retrieval route in the READ model and a visual/fact route in the MATH

model. The fourth Processing factor in each model was representative of Phonological Processing in the READ model and Algorithmic Processing in the MATH model. The results of the four factor READ and MATH models confirmed that each factor in each model was significantly representative of common measurement variance, and that the shared variance between each of the four factors in each model was also significant – representing a strong partnership between each of the four factors.

Confirmation was found for the second goal proposing a READ and MATH cognitive processing system based on research from the cognitive functional neurobiological literature on children with and without reading and/or math learning disabilities. It was proposed that this system includes an automatic visual route (orthographic or fact) a common cognitive process underlying reading and math acquisition, requiring the ability to rapidly identify the sound or name associated with visual information (e.g., familiar letters, digits, words, and math facts). When words and facts are unfamiliar or not automatically identifiable as whole forms, more advanced processing – such as phonological processing (awareness and decoding) and algorithmic processing (calculation and procedure) are employed.

These higher order processes first capitalize on what part of the word or fact has been automatically identified. Then working memory span can apply verbal rehearsal and/or visualization strategies to keep the familiar and unfamiliar parts ‘online’ in a working order. The more automatically information is identified (e.g., immediately reading a whole word form, or identifying the solution to a math fact), the more capacity the working memory system has for processing. The capacity of working memory span places limits on the amount the higher-order processes can simultaneously keep online to ‘work on.’ Verbal and nonverbal reasoning can also be employed to enhance problem-solving, and both of the SEM

models confirmed that these are vital partners that are also significantly intercorrelated with automatic, working memory span, and processing factors.

These findings stress the importance of developing theoretical models that map onto our understanding of how the brain operates as a neurological system that can be associated with underlying cognitive processing profiles associated with reading and/or math learning disabilities. These findings signal a need for assessments that not only look at the impact of independent cognitive processing deficits and their relation to academic skill, but also address the influence of one faulty cognitive process on the system and its collaborative effect on academic skill. These findings also stress the importance of continuing to evaluate the role of IQ, as measuring specific cognitive processes, and investigating their role as such in learning disabilities. These cognitive processes (e.g., vocabulary and verbal/nonverbal reasoning) appear to ‘work’ uniquely and in collaboration with other vital automatic, processing, and working memory processes underlying reading and math acquisition. This observation offers a different perspective on the role of IQ in the assessment of reading and math disabilities, one that requires more refined investigation.

### Part III

#### *Regression Analyses*

With the statistical advantage of sequestering error variance in the SEM models, the conceptual advantage to developing the READ and MATH models was that they provided solid theoretically-derived factors representing common measurement variance for automatic, working memory span, processing, and IQ or verbal/nonverbal reasoning. The third part of the study used stepwise regression to explore the extent to which each of these composites/cognitive processes predicted each group’s performance on reading and math

achievement tests. The findings enlightened our understanding of what cognitive processes (strong or weak) might contribute to each group's achievement, again allowing potential identification of cognitive processes that may require remediation.

While there may appear to be many stepwise regression equations that were run, the F value for all of the equations reached significance at a  $p < .01$  level, indicating extremely strong and reliable results. While it may be argued that an Enter method could have been used to get a more valid estimate of the total variance accounted for by one or more of the composites, this method also runs the risk of entering in a second factor due simply to its' significant correlation with the first; it may be that the second factor does not necessarily account for more unique variance. As an example, using the Enter method, Automatic (RAN/Words) and Phonological Processing might enter into the regression equation together and account for 50% of the total variance in LWID, when stepwise regression showed that Automatic (RAN//Words) accounted for 46% of the variance and Phonological Processing accounted for 4%. Using the Enter method in this particular example, Phonological Processing entered the equation with Automatic (RAN/Words) due to their high correlation. The READ and MATH SEMs already confirmed that the intercorrelations between each of the composites were highly significant. The main goal was not to predict as much variance as possible by using an Enter method, but to group variables into valid composites to explore which composite/cognitive process predicted the achievement level for each group, and in what order/step using stepwise regression.

*Predicting reading achievement in good readers.* Using the latent composites from the SEM READ and MATH models to predict reading achievement with the READ factors, the ND good readers appeared to rely on their more automatic visual/orthographic route and

solid nonverbal/verbal reasoning to achieve age-appropriate levels on LWID. With the MATH factors, visual Automatic RAN/Facts did not predict LWID for this group; however their accurate algorithmic processing did predict LWID, and appeared a strong measure of more advanced levels of processing for this group. Thus higher levels of processing on two composites (verbal/nonverbal reasoning and algorithmic processing) both predicted LWID for the ND good reader group.

Among the READ factors, phonological processing accuracy predicted decoding of nonwords on WA. When the MATH factors were entered, algorithmic processing did not enter and verbal/nonverbal reasoning did predict WA. Thus for decoding, this ‘good-at-everything group’ employed advanced phonological processing skills that did not appear to overlap with algorithmic processing. This suggests that phonological processing is a unique reading skill. Notably, this group was the only group to employ verbal/nonverbal reasoning to read and decode, suggesting their higher order processing advantage over all disability groups.

While the MD good readers had similar performance on LWID and WA as the ND good readers, it appeared that they used the opposite pattern of processes. Using READ factors they appeared to rely more on solid phonological processing and then automatic RAN/Words to reach age-appropriate performance on LWID, and visual automatic RAN/Words to decode nonwords on WA. Using the MATH factors, working memory span predicted LWID and their weaker RAN/Facts predicted WA.

This finding suggests that the ND good readers employed more appropriate skills (e.g., automatic/orthographic route for LWID, and phonological processing for WA) along with advanced reasoning relative to the MD good readers who had to phonologically process

words on LWID and pull from the automatic/orthographic route for WA, and who did not apply advanced reasoning skills. It is speculated that reading may not have been as ‘clean’ a process for the MD good readers.

*Predicting reading achievement in poor readers.* For the RD poor readers, using the READ factors their much weaker automatic RAN/Words predicted their below average performance on LWID and on WA. Advanced phonological processing was not employed by this group. Compared to the good readers, no MATH composites predicted LWID, and the RD group’s accurate algorithmic processing accounted for only 11% of the variance in WA, suggesting at least some level of processing. For the comorbid RD+MD group, who were ‘weak-at-everything’, their very limited automatic RAN/Words and weaker working memory span accounted for their similarly low scores on LWID, while there far less accurate phonological processing accounted for their low performance on WA.

Interestingly, when the MATH composites were entered, the comorbid poor readers were the only group to have their severely compromised visual automatic RAN/facts route predict LWID and their working memory span predict WA. These results suggest a potential overlap in faulty automatic visual retrieval routes for basic word and fact stores in the comorbid group. It also suggests that decoding was a much more taxing process in which they had to break down and attempt to hold online even the most basic grapheme-phoneme correspondences to read and decode words.

*Predicting math fluency: potential overlap in automatic visual/orthographic and visual/fact routes for good and poor readers and/or mathematicians.* An overlap in automatic visual retrieval routes (visual/orthographic and visual/fact) was also observed on Math Fluency, a test on which all disability groups were similarly weak. Also, for all four groups,

when the READ factors were used, automatic RAN/Words predicted Math Fluency, and when the MATH factors were used, automatic RAN/Facts predicted Math Fluency. It is proposed that overlap in automatic visual/orthographic and visual/facts may occur for very basic visual information and that this more automatic for the ND good readers, less so for the single disability groups, and even less so for the poor readers. In fact, in addition to RAN/Facts, weak working memory span predicted Math Fluency for the RD group and in addition to RAN/Words; weak phonological processing predicted Math Fluency for the RD+MD group.

The finding that RAN/Words would predict a Math Fluency task might initially seem implausible from an education/skill instruction perspective. However, it appears a viable hypothesis when looked at from a cognitive-neurofunctional perspective. It is proposed that automatic visual information in the reading and math domains (e.g., word forms and math facts) may be supported by similar underlying cognitive processes, namely automatic retrieval of a visual form, that are potentially housed within similar neurobiological areas. If this hypothesis proved reliable, educational programming/remediation could be targeted at unique or overlapping visual routes (orthographic and/or fact), along with areas of the curriculum that deficits in these routes might further impede (e.g., working memory span, or phonological or algorithmic processing).

*Predicting calculation and applied problems in good mathematicians (ND and RD).*

For the ND good mathematicians, good verbal/nonverbal reasoning and very automatic RAN/Words predicted Calculation. For the RD good mathematicians, good verbal/nonverbal reasoning never entered into the regression equation. In spite of good or poor reading, accurate algorithmic processing predicted Calculation for both good mathematician groups

(ND and RD) when the MATH factors were used. Solid verbal/nonverbal reasoning also predicted the ND group's age-appropriate performance on Applied Problems, in addition to algorithmic processing when the MATH factors were entered. Notably, only algorithmic processing predicted the RD group's age-appropriate performance on Applied Problems. Similarly, when reading achievement was predicted reasoning skills did not appear to be employed by the RD group.

*Predicting calculation and applied problems in poor mathematicians (MD and RD+MD).* For the MD group, when READ and MATH factors were entered, only their solid verbal/nonverbal reasoning predicted low Calculation scores and their age-appropriate scores on Applied Problems. Using the MATH factors, compared to the good mathematicians, the MD group's weak algorithmic processing did not predict their Calculation and Applied Problems scores. This suggests that this group possibly capitalized on good reasoning, reading, and aids (e.g., pencil and paper and visual pictures) to compensate for weaker algorithmic processing when solving Applied Problems. For the RD+MD group, their very weak algorithmic processing and relatively weaker verbal/nonverbal reasoning predicted their poor Calculation scores while their weaker verbal/nonverbal reasoning and weaker automatic RAN/Facts predicted their below average performance on Applied Problems. Compared to the MD good readers, the RD+MD group also had weak reading skills that may have impacted their lower performance on these tasks.

One final observation was that when the READ factors were used to predict Calculation or Applied Problems, unlike when Math Fluency was predicted, automatic visual/orthographic (RAN/Words) were not predictors for any of the groups. This evidence further supports speculation that visual/orthographic and visual/fact routes appear to overlap

at a very basic automatic/visual skill level. That accurate phonological processing did not predict any of the math tests for the good readers (ND and MD), but more accurate algorithmic processing predicted LWID and WA for good readers (ND and RD, respectively) continues to suggest that good phonological processing is a very unique skill related to good reading and that the processes in algorithmic processing (as measured in this study) may not be as unique to math.

### Future Implications

These results contribute to our understanding of the underlying cognitive processes that are unique and shared by the present elementary aged students who were classified with single and comorbid reading and math disabilities. By comparing their profiles to ‘good-at-everything’ readers, a more refined understanding of cognitive strengths and weakness associated with good and poor reading and math achievement was provided. As mentioned earlier, this profiling could be of value to psychologists when evaluating single versus comorbid reading and math disabilities.

Structural equation modelling represented solid composites in reading and math and supported the significant and dynamic partnership between automatic visual routes, working memory span, advanced processing, and IQ or verbal/nonverbal reasoning. It is important to look at these significant cognitive processes and how they uniquely and in partnership contribute to good and poor reading and math acquisition. Such a perspective allows a closer approximation to how the brain works as a system and demonstrates that cognitive processes never operate in complete isolation.

This dynamic relation between cognitive processes (as evidenced by the READ and MATH SEMs) could be used to specify the assessment tools needed for diagnostics, regular,

and special educational programming. Assessment should sample associated underlying cognitive processes and their interrelationship to functionally explain single and comorbid reading and math learning disabilities. On this basis, more informed evidence-based programming could be developed. Instead of using regression analyses, future research should increase the number of children in each group and allow READ and MATH SEMs to be designed to predict each achievement test within each SEM model. Such efforts could elucidate the relation between the four factors in each model and how they work together when predicting reading and math achievement.

That said, using the READ and MATH composites as predictors of reading and math achievement in RD, MD, and comorbid groups, the present findings contribute to a new perspective on learning disabilities. In the present research, the list-of-deficits approach to studying learning disabilities is abandoned in favour of a multiple-step level of analysis. By theoretically modelling potential cognitive neurobiological systems in reading and math using SEMs, the independent and collaborative functions of the associated underlying cognitive processes of reading and math skill development were explored. The regression analyses provided further information about which of the cognitive processes might help to functionally explain good and poor readers and/or mathematicians different achievement levels. These analyses also identified different degrees of potential overlap in basic automatic visual/orthographic and visual/fact routes for good and poor readers and/or mathematicians.

These data provide fertile ground for larger-scale studies of the cognitive, behavioural, and functional neurobiological profiles of academic learning in atypical learners. Several new functional neuroimaging research findings are now providing

converging fMRI evidence about the unique and possibly shared neurobiological systems that support cognitive processes that are atypical in children and adults with reading disabilities (Pugh et al., 2005; Shaywitz et al., 2007) and with math disabilities (see Fletcher, Lyon, Fuchs, and Barnes (2007, for review)). Within the reading domain, research shows the ‘normalization’ of reading-related activation profiles with effective remediation (Just, 2007; Pugh et al., 2005; Shaywitz et al., 2007; Simos et al., 2002). Future research could further investigate pre- and post- math-related activation profiles following targeted math remediation.

With replication and extension of the present findings, future investigations may be able to customize remedial programs that target the specific cognitive deficits of single and comorbid reading and math disabilities, and allow for better evidence-based monitoring of the impact of such programs on reading and math acquisition in atypical learners. Further observation of fMRI activation during tasks measuring the cognitive strengths and weaknesses associated with no disability and reading, math, and comorbid reading and math disabilities, could provide data on associated functional neurobiological systems and investigate their unique and possibly shared resources.

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