A Neuroeducational Approach to Defining the Cognitive Profile of Comorbid Math and Reading Disabilities

by

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of

Master of Science

in

Neuroscience

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Ottawa, Ontario

Abstract

Psychoeducational studies have shown that the comorbidity between reading disability and mathematical disability is relatively high but the neuroanatomical substrates that may underlie this comorbidity have not been reliably identified. We developed a novel neuroeducational approach to bridge the corresponding concepts on learning disabilities in the neuropsychological and psychoeducational fields. First, we assessed the cognitive profiles of individuals with reading, mathematical and both disabilities (comorbid group), using psychoeducational tests also often used in neuropsychological test batteries. Second, we performed a systematic review of current literature on the neuroanatomical substrates of dyslexia and dyscalculia. Third, we mapped the cognitive profiles to the neuroanatomical substrates plausibly shared with dyslexia and dyscalculia. The comorbid group exhibited reading deficits similar to those shown by individuals having reading disability alone, which may be associated with atypical function at the *left inferior frontal* and *left fusiform gyri* similar to the math-disabled group; they also exhibited deficits in quantitative reasoning, which may be associated with a bilateral atypical function of the *intraparietal sulci*. Further deficits related to verbal working memory and semantic memory were exclusive to the comorbid group. The current approach suggests that impaired phonological, numerical, semantic, and working memory processes may be associated with atypical function of the *left angular gyrus* in both reading and mathematical disabilities.

Acknowledgements

I'd like to begin by thanking my thesis supervisor, Dr. Amedeo D'Angiulli, for his dedication to my success and ongoing support in my career. He has been instrumental in my development as a researcher over the past two years, and has always pushed me to strive for more knowledge and to never settle in my work. Thank you, Amedeo, for being patient with me, and for all the times you've had explain a concept over and over again.

I'd like to thank my thesis committee members, Dr. Natalina Salmaso, Dr. Patrice Smith, Dr. Shawn Hayley and Dr. John Logan. Thank you, Dr. Smith, for bringing up thoughtful, real-world questions about my research. Thank you, Natalina, for providing a clinical perspective on my research and always challenging my preconceived notions about neuropsychology. Thank you, Dr. Hayley, for always having an open door to address my questions and concerns, and for helping me with my critical thinking and presentation skills. Thank you, Dr. Logan, for making me feel confident in the preparation for my thesis defence, and providing me with valuable feedback.

I'd also like to thank Dr. John Stead and Dr. Hymie Anisman for their mentorship at various times over the past two years. Thank you, John, for always looking out for me and being dedicated to my success. Thank you Hymie, for always engaging me in fun conversation and making sure that I'm surviving graduate school.

I'd like to express my sincere gratitude to Diane Trenouth, our absolutely incredible Graduate Administrator. From the day I applied to the program, to the day I submitted my thesis, she has been working on my behalf to get things done at a moment's notice. Thank you, Diane, for having favour on me.

I'd like to thank my fellow students in the NICER Lab, Matt Buchanan, Nina Hedayati, and Faisa Omer. Matt, thank you for the all the opportunities you've provided me with, and for always encouraging me to get more skills and develop as a neuropsychologist. Nina, thank you for sharing your time and space with me on so many occasions, and enduring the struggle of application deadlines and thesis milestones alongside me. Faisa, thanks for keeping it 100% real with me and always having my back! You bring so much life and energy to the lab and I'm grateful for our friendship. I'd also like to thank Patricia Van Roon, Eddy Yakubovich, Korey MacDougall, Kylie Schibli and Christina Ou for welcoming me into the lab and providing me with guidance in my early days.

I'd like to highlight the contribution of my undergraduate volunteers, who did the little things that made a big difference in making this thesis possible. Darren Kenney and Erica Martin, thank you both for your work in helping me complete the database, and for being so willing to help me catch any details I was missing. Moe Abou-El-Daoule and Dominique Dupont, thank you for listening to my ideas over and over and over again and for your immense help in getting my follow-up study off the ground.

Thank you to Professor Ahmed Almuskut, who taught me most of what I know about statistics! A special shout out to my fellow grad students Kaylyn Dixon, Sam Coates, Sam Chin, Robbie Woods, and Marc Bedard for making life fun and interesting in stats class, and thanks to Usha Shanmugalingam and Sherine Elsharnouby for always making sure I'm doing ok.

Thank you to my family for being supportive of my goals. Thank you to my brother, Julian, for riding alongside me from my post-undergrad job hunting days to graduation. We've been through so much together, it's incredible to see that we're both at the cusp of new adventures. Shout out to the Shattsss and my Benjamin Ave. Church family for keeping me prayed up these past two years! Exodus 14:14. Thank you to my fiancé, my #1 supporter, my cheerleader, Fredrica St. Hilaire. You've been there for me on so many late nights when I felt like I should quit; you always know the right words to say when I'm at my lowest. You're the real MVP.

Last but certainly not least, I'd like to thank my parents, Dr. Gerald Grant and Joan Grant, for their immense support throughout my academic career. I will never be able to repay the incredible sacrifices you've made to ensure my success; no amount of words can accurately describe how blessed I am to be your son. I owe this degree and all of my accomplishments—both past and future—to you.

Table of Contents

List of Tables

List of Figures

List of Appendices

Introduction

The classification, diagnosis, and treatment of learning disabilities are important research topics in both psychoeducational and neuropsychological literature. Researchers in these two fields often measure similar constructs, but use differing approaches to examine individuals with learning disabilities. As a result, each field has produced different concepts and theories over time, and has led to a disconnect between the identification of learning disabilities in educational settings and the identification of learning disabilities based on neuroscientific evidence. Furthermore, the identification and development of comorbid learning disabilities is a prevalent topic in psychoeducational literature, but is understudied in neuropsychology; a testable model of the neuroanatomical substrates of comorbidity is greatly needed. We developed a novel *neuroeducational* approach to bridge the corresponding concepts on learning disabilities in the psychoeducational and neuropsychological fields. That is, we established the cognitive profiles of individuals with learning disabilities using psychoeducational measurements and then we related these profiles to the neuroanatomical correlates of dyslexia and dyscalculia based on an exhaustive systematic review of the neuroimaging literature. The resulting neuroeducational model of comorbidity fills the gaps in knowledge in both Education and Neuroscience, creating a two-way transdisciplinary reciprocal contribution.

1.1 Learning disabilities

Learning disabilities are a type of neurodevelopmental disorders that impede the acquisition, retention, or application of verbal or nonverbal information, affecting a person's ability to use specific cognitive skills (Craig & Phillips, 2015; Tannock, 2014). Learning disabilities are characterized by unexpected difficulties in cognition and applying academic skills that are not produced by intellectual disability, impaired visual or auditory perception, or influenced by inadequate academic instruction (American Psychiatric Association, 2013; Light & DeFries, 1995; Lyon et al., 2001). Learning disabilities are lifelong conditions; the initial can be detected in early childhood, but a formal diagnosis is not typically made until a person reaches secondary or postsecondary education (Silver et al., 2008b). Children with a learning disability are at greater risk for lower socioeconomic outcomes later in life, including higher rates of high school dropout, higher levels of psychological distress, higher rates of unemployment (American Psychiatric Association, 2013; Candace Cortiella & Horowitz, 2014; Silver et al., 2008b).

Three types of learning disabilities are particularly prevalent across all age groups worldwide (American Psychiatric Association, 2013; Hulme & Snowling, 2009; Kail & Barnfield, 2014). The most pervasive and well-known is *reading disability*, a specific difficulty in learning to read, interpret, and manipulate written words, also known as *dyslexia* (obtained from the Greek *dy*s- meaning 'difficult', and *-lexis* meaning 'word'). The second is *mathematical disability*, a specific difficulty in learning arithmetic and performing mental calculations, also known as *dyscalculia* (obtained from the Latin *calculare* meaning 'to calculate') The third is *dysgraphia* (from the Greek *graphos* meaning 'drawn' or 'written'), a specific difficulty learning to express one's thoughts in writing. These learning disabilities occur on a continuum—meaning that there is a wide range of symptom severity and cognitive deficits that fit the diagnostic criteria for a specific learning disorder (Branum-Martin, Fletcher, & Stuebing, 2012).

Individuals with comorbid learning disabilities face additional barriers to successful learning. Recent studies have reported that math and reading disabilities co-occur at a higher rate than would be expected by pure statistical chance (Landerl, Fussenegger, Moll, &

Willburger, 2009; Wilson et al., 2015); but the currently available research on comorbid math and reading disabilities and their developmental origins is far from exhaustive. Empirical research on math disability is substantially underrepresented in research literature; as recently as 2007, a systematic review of the U.S. Department of Education's Educational Research Information Center (ERIC) database revealed that the number of published studies on reading disability outnumbered the number of studies on math disability by a ratio of 14 to 1 (Gersten, Clarke, & Mazzocco, 2007). This disparity in knowledge translates into disproportionate diagnoses and asymmetric interventions for individuals with comorbid math and reading disabilities. Students with comorbid learning disabilities often do not receive an appropriate neuropsychological evaluation when needed (Silver et al., 2008b). For those who do receive some form of educational assessment or intelligence testing, the typical educational interventions that are employed concentrate on improving reading ability; any other difficulties are relegated to overall deficits in intelligence or comprehension, and their math disabilities are left unaddressed. Furthermore, the lack of public awareness about math disabilities makes it difficult for parents and educators—those who are best-positioned to identify learning disabilities early in development—to recognize and report a child's subtle and specific difficulties with arithmetic and mental calculations. Few studies have investigated the effectiveness of educational interventions for individuals with comorbid math and reading disabilities (Fuchs, Fuchs, & Prentice, 2004; Mann Koepke & Miller, 2013), and little is known about the developmental trajectories or changes in neurological function that lead to comorbid learning disabilities (Dandache, Wouters, & Ghesquière, 2014). Therefore, defining a robust neuroeducational model of dyslexia-dyscalculia comorbidity is a top priority for the early identification and treatment of learning disabilities (Norton, Beach, & Gabrieli, 2015; Silver et al., 2006, 2008b).

1.2 The psychoeducational approach to identifying learning disabilities

Learning disabilities are typically first identified in educations in one academic settings (Cortiella & Horowitz, 2014). When a student demonstrates persistent and pervasive difficulties in a particular academic area, a special education teacher may recommend that the student undergo a psychoeducational evaluation. The psychoeducational evaluation is the traditional method of classifying and identifying learning disabilities; the goal of the evaluation is to examine the student's strengths and weaknesses in various ability domains (Flanagan, Fiorello, & Ortiz, 2010). In this approach, a special education teacher will determine the presence and severity of a learning disability based on the student's performance on standardized tests of general academic achievement (Branum-Martin et al., 2012), and will determine if the student qualifies for special education or remedial training (Reed, 1976). A psychoeducational assessment typically consists of obtaining an IQ score and completing a few domain-specific standardized tests—psychometric measures that directly assess concepts and abilities in reading, writing, or arithmetic (Poland et al., 1983; Silver et al., 2008).

In the psychoeducational approach, the IQ-achievement discrepancy model provides the framework for identifying an unexpected difficulty with learning. In order for an individual to be classified as having a learning disability, the discrepancy model requires that there is a significant discrepancy (usually 1.5 standard deviations) between the person's academic ability or potential (defined by the IQ score) and academic achievement (as defined by their scores on a general reading or math test). This model rests on the assumption that intelligence tests and domain-specific psychoeducational tests provide independent measures for different cognitive processes (Sattler & Hoge, 2006), and regrettably exclude the possibility of identifying learning disabilities in people with intellectual disabilities (Siegel, 2006).

1.3 The neuropsychological approach to identifying learning disabilities

In comparison to the psychoeducational evaluations, neuropsychological assessments are greater in the depth of the assessment. They are more precisely-tuned to examine the specific cognitive deficits (such a phonological processing deficits) that underlie learning disabilities. A neuropsychological assessment is performed by a licenced clinical neuropsychologist, a doctoral-level clinician who combines their understanding of brain anatomy, cognitive neuroscience, and neurodevelopment to trace the neurological correlates of differences in specific cognitive abilities (Silver et al., 2006).

Secondly, neuropsychological assessments are greater in the breadth of the assessment. In contrast to a psychoeducational evaluation (which typically consists of an IQ score and a few standardized tests), a full neuropsychological assessment includes a structured clinical interview with the client (and an interview of the client's family and/or significant others, if possible), a review of the client's relevant medical records, and the administration of tests that measure domain-general functions such as selective attention, sensory perception, fine motor skills, visuospatial reasoning, and working memory (Silver et al., 2006). The clinical neuropsychologist will use all of this information to make a specific diagnosis of the client's learning disability, instead of relying on psychometric measures alone.

Third, the interpretation of test scores from a neuropsychological assessment is guided by different principles than in a psychoeducational evaluation. Instead of applying the IQ-discrepancy model as in psychoeducational approach, clinical neuropsychologists define the severity of a learning disability by introducing a cut-off threshold on the tail end of a distribution of academic achievement (Branum-Martin et al., 2012). While cut-off points are useful for providing a diagnosis after an assessment, they do not precisely reflect the neurobiological correlates of a learning disability (Shaywitz, 2001; Siegel, 2006) because they emphasize normativity and address pragmatic issues related to early intervention given the limits of current causal models.

Novel neuropsychological methods to identifying and providing interventions for learning disabilities have emerged in recent years. *Neuroprognosis*—the use of functional neuroimaging to predict the development of disorders—has shown some promise for children with dyslexia. Analysis of activation patterns during phonological processing tasks has been used to predict if a dyslexic child will improve in reading fluency 2.5 years later, with 90% accuracy (Hoeft et al., 2011). In addition, transcranial direct current stimulation (tDCS), transcranial magnetic stimulation (TMS), and EEG neurofeedback have been used to remediate phonological deficits in adults with dyslexia (Costanzo et al., 2013; Heth & Lavidor, 2015; Sadeghi & Nazari, 2015). These technologies are still in their infancy; in order to provide more effective interventions for people with learning disabilities, more knowledge is needed about the neural correlates of learning disabilities, their neurodevelopmental trajectory, and the relationship between altered neurobiology and its effects on specific cognitive abilities.
The identification of math and reading disabilities is a predominant topic in n*euroeducation*—an emerging field at the intersection of neuropsychology and psychoeducational research (Anderson, M., & Della Sala, 2012; Ansari & Coch, 2016; Gabrieli, 2009). The goals of neuroeducation are to develop curricula and teaching methods that are based on a scientific understanding of neural mechanisms of learning (Coch & Ansari, 2009; Howard-Jones et al., 2015), and to dissuade *neuromyths*—false claims about brain function that have arisen from mistranslations of scientific findings (Goswami, 2006), such as the neural basis of learning

styles, or the belief that specific lateralized functions correspond with rigid diagnoses of learning ability (teaching a student that they are 'right-brained' or 'left-brained'). Bridging the gaps of knowledge in education and neuroscience is best achieved via direct, bidirectional collaboration between educators and neuroscience researchers, without relying on commercial intermediaries in the 'brain-based learning industry' who may profit from selling learning technologies based on neuromyths (Goswami, 2006). This is a central theme of the current research; linking corresponding constructs in education and neuroscience can provide a better explanation of the biological and psychological factors that yield poor academic outcomes seen in individuals with learning disabilities. By examining the cognitive profiles of individuals with dyslexia and dyscalculia, and mapping the observed deficits to their neuroanatomical correlates from existing research, the neuroeducational model proposed in the current research provides educators and neuroscience researchers with a framework for designing more effective teaching interventions for individuals with comorbid learning disabilities.

1.4 The neuropsychology of dyslexia

Approximately 10% of North American children live with developmental dyslexia (Dickman et al., 2002; Lyon et al., 2003), a specific learning disorder characterized by unexpected difficulties with reading fluency that are not better explained by visual or cognitive impairments, psychosocial challenges, or poor language instruction. Dyslexia affects males and females at equal rates (Peterson & Pennington, 2015), and is typically demonstrated in the form inaccurate or effortful reading, poor spelling ability, and the avoidance of leisure or work-related activities that involve reading (American Psychiatric Association, 2013; Dickman et al., 2002). The majority of the literature on learning disabilities frames dyslexia as the behavioral product of deficits in specific cognitive skills; but a growing body of research support the notion that dyslexia is a different way of learning—and not just a disorder—with its advantages and disadvantages (Paul, 2012; Schneps, Rose, & Fischer, 2007).

Differences in reading ability between individuals with dyslexia and normal readers can be reliably detected as early as the first grade (Ferrer et al., 2015) using neuropsychological tests that specifically measure pre-reading phonological skills. In contrast, traditional reading achievement tests for identifying dyslexia—which follow the IQ-discrepancy approach—can only be administered to children ages 9 and older, delaying any potential interventions for reading disability. As a result, many dyslexic children endure an additional two-to-three years of poor academic performance and psychosocial stress before being considered eligible for an academic evaluation (Lyon et al., 2001; Silver et al., 2006) .

1.4.1 The cognitive profile of reading disability and dyslexia

Dyslexia is characterized by impaired *reading fluency*. For individuals with dyslexia, reading written passages is a pervasive challenge—whether they are reading familiar words within their age-appropriate lexicon, or attempting to decode complex low-frequency words for the first time. There are several overlapping theories about the cognitive processes that are affected in developmental dyslexia, each one presenting different cognitive processes whose dysfunction leads to impaired reading fluency (Ramus, 2003). Three theories in particular have garnered widespread support in current research literature: the *phonological deficit theory*, the *visual deficit theory*, and the *double-deficit theory*.

The *phonological deficit* theory of dyslexia is the most widely-promoted and well-established theory in dyslexia research (Peterson & Pennington, 2015; Vellutino, Fletcher, Snowling, & Scanlon, 2004). The term *phonological* refers to *phonemes,* which are individual units of language that represent unique sounds within a particular language. The English language, for example, contains 44 phonemes (made up of consonants, vowels, and diagraphs), a series of unique sounds that can be used to create words, and can be exchanged individually to alter the meaning of a word. The term *phonological processing refers to* the cognitive ability to segment a word into individual phonemes. The *phonological deficit theory* proposes that the core impairment in dyslexia is a deficit in phonological processing—an innate, pervasive difficulty with forming associations between phoneme combinations and the correct corresponding sounds, known as grapheme–phoneme correspondence. (Shaywitz, 1998; Snowling, 1981). Reading fluency relies on the ability to combine individual phonemes to produce meaning. Normal readers form long-term phonological representations of words, which facilitates more fluent reading ability. When they view a familiar word, normal readers can retrieve their phonological representation of the word and bypass the decoding of individual phonemes (Coltheart, Curtis, Atkins, & Haller, 1993). In support of the phonological deficit theory, deficits in phonological processing can be identified early in development (Felton, 1992; Ferrer et al., 2015), persist into adulthood (Felton, Naylor, & Wood, 1990; Wilson & Lesaux, 2001). Dyslexic children exhibit marked difficulties in manipulating *pseudowords* (nonsensical words made up of valid phonemes in a particular language), and display poor reading fluency when asked to read written words, but not when the words are read to them by another individual (Lyon et al., 2003; Norton et al., 2015). In addition, specific training to improve phonological processing leads to significant improvements in reading ability (Alexander, Andersen, Heilman, Voeller, & Torgesen, 1991; Ball & Blachman, 1991).

The *double-deficit theory of dyslexia* builds on the notions presented in the phonological deficit theory. In addition to impaired phonological processing, this theory suggests dyslexia is characterized by a deficit in rapid automatized naming (RAN). Rapid automatized naming is the measure of how quickly an individual can recognize and name aloud a series of familiar objects, pictures, colors, or symbols, or letters (Wolf & Bowers, 1999). Recent studies have suggested that poor RAN performance may reflect impaired functional connectivity between brain structures that control visual processing and speech. However, poor RAN performance in sight-word reading is not exclusive to individuals with reading disabilities, and phonological deficits are more reliably identified in individuals with dyslexia and are more likely to underlie difficulties in recognizing words (Nelson, 2015; Vukovic & Siegel, 2006).

The visual deficit theory states that reading disabilities arise due to atypical development of the visual system, disrupting the processing of visual information from letters and words in written text. In some neuropsychological studies, individuals with reading disabilities have been shown exhibit impaired temporal processing, atypical eye movement regulation, and more frequent visual scanning errors in comparison to normal readers (Eden, VanMeter, Rumsey, & Zeffiro, 1996). While below-average performance on visual attention tasks in preschool has been shown to predict reading disability (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012), it is unclear whether a visual system deficit is a root cause or a result of long-term reading disabilities (Olulade, Napoliello, & Eden, 2013), and seems to contradict recent findings of heightened visuospatial reasoning in dyslexic adults (Bacon & Handley, 2014; Schneps et al., 2007; von Károlyi, Winner, Gray, & Sherman, 2003). Proponents of this theory do not view visual deficits as the only possible cause of dyslexia, but rather as a complementary explanation that accounts for the cognitive deficits seen in individuals with reading disabilities.

1.4.2 The neuroanatomical correlates of dyslexia

Reading is a multimodal process that relies on input from the brain's visual and auditory systems to recognize symbols within a language, decode them into phonemes, and assign meaning to written words and sentences. Converging evidence from functional neuroimaging studies has pinpointed three neuroanatomical regions in the left hemisphere primarily facilitate the processing of written words: the *left inferior frontal gyrus*, the *fusiform gyrus*, and *tempororparietal parietal junction* (displayed in Figure 1). The inferior frontal gyrus (Brodmann area 44 and 45), which contains *Broca's area*, is well-known in the neuropsychology literature for its role mediating in speech production, but is less recognized for its role in processing phoneme sequences and phonological segmentation (Berker, Berker, & Smith, 1986; Burton, Small, & Blumstein, 1997; Flinker et al., 2015). The fusiform gyrus (Brodmann Area 37, also known as the *occipitotemporal gyrus*) contains the *Visual Word Form area*, which enables humans to distinguish between the symbols that form letters and numbers, and symbols that are otherwise arbitrary shapes (Dehaene & Cohen, 2016; Roberts et al., 2013). The *temporoparietal junction* (a group of structures including the *angular gyrus*, *supramarginal gyrus*, and the *superior temporal gyrus*) facilitates semantic processing and is also involved the analysis of phoneme sequences (Graves, Binder, Desai, Conant, & Seidenberg, 2010; Shaywitz, 2001; Shaywitz & Shaywitz, 2008).

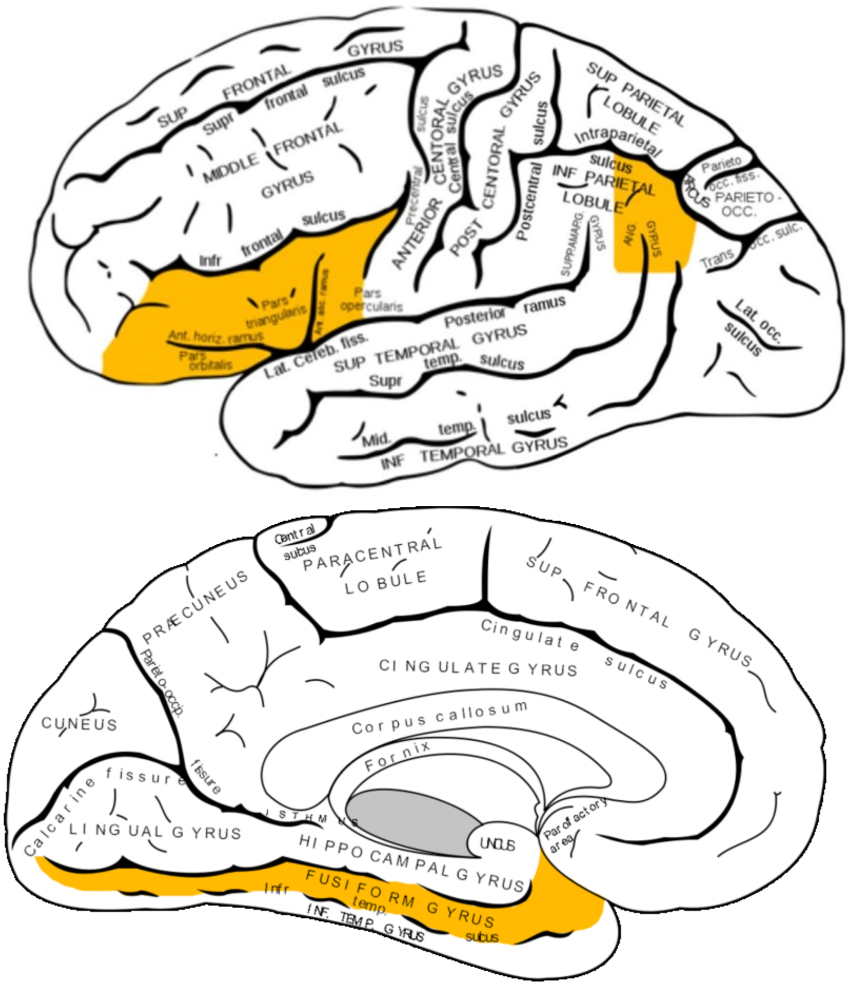


Figure 1. Three neuroanatomical structures of the left hemisphere language processing network (Gray, 2000). At the top, the left inferior frontal gyrus and the left angular gyrus are highlighted in this lateral view of the cerebral cortex. At the bottom, a sagittal view of the cerebral cortex shows the left fusiform gyrus.

Dyslexia is associated with atypical development of the left hemisphere language network (Lyon et al., 2003; Peterson & Pennington, 2015; Richlan, 2012). In comparison to age-matched controls with typical reading ability, individuals with dyslexia show atypical physiological activity and white-matter connectivity have been shown in a several frontal, parietal, and temporal structures in their dominant hemisphere, which have been identified with moderate consistency across world languages (Paulesu et al., 2001; Hu et al., 2010). The most consistent findings have been reported in studies that used functional neuroimaging to examine the neural correlates of phonological decoding. When asked to or asked to decode words aloud, individuals with dyslexia typically exhibit lower cerebral blood oxygenation at the posterior regions of the language network—usually the left *fusiform gyrus* and the structures of the left *temporoparietal junction* (Norton et al., 2015; B. A. Shaywitz, 2001). Two more recent meta-analyses of neuroimaging studies on dyslexia have identified a variety of regions that exhibit atypical hypoactivity during reading tasks, including the bilateral *superior temporal gyri*, left *middle* and left *inferior temporal gyri*, left *precuneus*, left *thalamus*, *right postcentral gyrus*, and the *right fusiform gyrus* (Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Richlan, Kronbichler, & Wimmer, 2009).

The compensatory mechanisms for dyslexia are not well understood. In some studies, individuals with dyslexia demonstrate greater physiological activation than controls at the left inferior frontal gyrus and right fusiform gyrus (Burton et al., 1997; B. A. Shaywitz, 2001); in others, the frontal and fusiform gyri show less activation in controls, while the right thalamus, primary motor cortex, and anterior insula show greater activation instead (Eden & Zeffiro, 1998; Richlan et al., 2009). To further complicate the matter, differences in activation at these regions do not correlate with differences in visuospatial reasoning, which has been proposed as a key compensatory mechanism in dyslexia (Schneps et al., 2007). A major challenge to research on reading disabilities is determining whether atypical physiological function at each region is due to the developmental trajectory of dyslexia itself, or if they are consequences of poor reading experience over the lifespan.

1.5 The neuropsychology of dyscalculia

Developmental dyscalculia is a specific learning disorder characterized by unexpected difficulties in processing numerical information and performing basic mathematical operations, impeding the acquisition of age-appropriate mathematical skills (American Psychiatric Association, 2013; Price & Ansari, 2013). Individuals with dyscalculia often exhibit a perseverant use of primitive calculation strategies in problem solving, below-average performance on mathematical achievement tests, as well as an aversion to or a pervasive difficulty with everyday tasks that involve numbers, such as time management and performing financial transactions (Candace Cortiella & Horowitz, 2014; Williams, 2012). It is estimated that dyscalculia affects 3-6% of the world population, (Shalev, Auerbach, Manor, & Gross-Tsur, 2000; Wilson, 2012), but dyscalculia is considerably unrepresented in research literature on learning disabilities (Gersten et al., 2007; Price & Ansari, 2015). Anywhere from 17% to 66% of individuals with dyscalculia also fit the diagnostic criteria for dyslexia (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013; Mann Koepke & Miller, 2013). These comorbid individuals appear to exhibit deficits in two different cognitive domains (Landerl et al., 2009; Wilson et al., 2015); their deficits in reading fluency are separate from deficits in numerical cognition. The neuroanatomical correlates that overlap in reading and math disabilities not been reliably identified.

1.5.1 The cognitive profile of mathematical disability and dyscalculia

Dyscalculia is characterized by impaired *number sense*, which refers to the intuitive ability to understand numbers and their magnitudes, the ability to quickly perform mental operations without writing out a procedure or relying on complex algorithms (Dehaene, 2001). Tasks that involve manipulating or estimating numerical quantities are persistently difficult for individuals with dyscalculia—everyday tasks such as correctly estimating the passage of time, or to intuitively, quickly, and correctly compare groups of objects presented visually.

It is hypothesized that humans form mental representations of numerical quantities using a *mental number line*, an imaginary line with a series of numbers ordered in ascending fashion. Following this theory, an individual can estimate the place any number or quantity on the number line and perform operations using their approximation of the number—a cognitive function known as *numerical magnitude processing* or the *approximate number system*. The acuity of a person's approximate number system can be examined using *numerical magnitude comparison* tasks with *non-symbolic* quantities (e.g. a group of dots) as opposed to symbolic Arabic digits (e.g. the number 9). In a non-symbolic numerical comparison task, the individual is asked to approximate the correct place for non-symbolic quantity (without counting each item one-by-one) on a visually-presented number line. A greater degree of error in the approximation of quantity is believed to indicate a deficit in numerical magnitude processing; this has been identified as the core deficit underlying impaired poor number sense developmental dyscalculia (Bugden & Ansari, 2015b; Butterworth, 2011). In comparison to typically-developing controls, children with dyscalculia demonstrate lower accuracy in approximating the number of non-symbolic items in a group, and lower accuracy in determining which group of items is greater in magnitude (Landerl, Bevan, & Butterworth, 2004; Mazzocco, Feigenson, & Halberda, 2011). Using number sense to make approximations of numerical quantities relies heavily on spatial representations of numbers (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013; Zago et al., 2001); as a result, individuals with dyscalculia often perform poorly on neuropsychological tests of visuospatial ability (Wilson et al., 2015).

1.5.2 The neuroanatomical correlates of dyscalculia

Functional neuroimaging studies have identified two parietal regions that facilitate the manipulation of numerical quantities: the bilateral *intraparietal sulci* and the left *angular gyrus*. The right and left *intraparietal sulci* (shown in Figure 2) are activated during numerical magnitude comparison tasks (Butterworth, 2011; Molko et al., 2003). In the left hemisphere, the *angular gyrus* facilitates the retrieval of arithmetic facts, such as the solutions to simple multiplications (Dehaene, Piazza, Pinel, & Cohen, 2003; Grabner et al., 2009). In the frontal lobe, the uniquely human ability to consciously reason about the non-numerical aspects mathematical tasks (such as choosing a strategy or arithmetic procedure to solve a word problem, or identifying errors or limitations in a problem) is mediated by the *prefrontal cortex* (Menon, Mackenzie, Rivera, & Reiss, 2002).

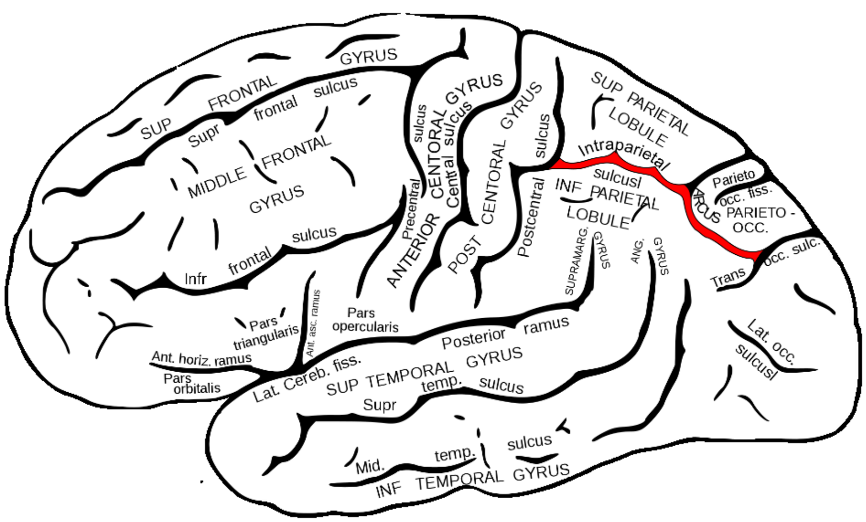


Figure 2. Lateral view of the left intraparietal sulcus (Gray, 2000). While several brain regions facilitate various aspects of mathematical cognition, intraparietal sulcus (IPS) is the primary activation site during tasks that test numerical magnitude processing.

While the neuroanatomical evidence of atypical brain function in developmental dyscalculia is not quite exhaustive, several functional neuroimaging studies have reported atypical activation patterns at the intraparietal sulci. In comparison to typically-developing children, children with dyscalculia have been shown to exhibit reduced activation at the right intraparietal sulcus when performing non-symbolic numerical comparison tasks (Price, Palmer, Battista, & Ansari, 2012). In addition, applying transcranial magnetic stimulation to the right intraparietal sulcus can severely impede performance on numerical magnitude tasks, artificially producing deficits that are equivalent to those observed in adults with dyscalculia (Cappelletti, Barth, Fregni, Spelke, & Pascual-Leone, 2007; Cohen Kadosh et al., 2007).

1.6 Research Questions & Hypotheses

The primary objective of this study was to outline a neuroeducational model of dyslexia-dyscalculia comorbidity—a framework for understanding the psychoeducational and neuropsychological characteristics of individuals with comorbid math and reading disabilities that can be tested for validity in future research. This model was established in three phases. In the first phase—using a psychoeducational approach—we examined the performance of individuals with math and reading disabilities on a series of psychoeducational tests, and drew conclusions about the specific cognitive deficits they exhibited. In the second phase—using a neuropsychological approach—we performed a systematic review of existing studies on the neuroanatomical correlates of dyslexia and dyscalculia, and identified key neuroanatomical structures whose abnormal function was reliably correlated with dyslexia or dyscalculia. In the third phase, we mapped the deficits as measured by psychoeducational tests to their most plausible neuroanatomical correlates obtained in the systematic review, creating a neuroeducational model of comorbidity that unites the broad psychoeducational definitions of math and reading disabilities with neuropsychological evidence of the biological characteristics of dyslexia and dyscalculia. This series of operations allowed us to build correspondence between the diagnostic tools used to identify learning disabilities in psychoeducational research and the neurodevelopmental theories of dyslexia and dyscalculia seen in neuropsychological literature.

In order to determine the cognitive profile of comorbid dyslexia-dyscalculia, the present study evaluated the performances of a sample population with math disability, reading disability, and dual math-and-reading disability as measured by a battery of psychoeducational tests. The statistical analysis of their psychoeducational outcomes were used to (i) determine if there were any measurable cognitive deficits that were unique (in nature or in magnitude) to the participants with comorbid reading-math comorbidity; (ii) determine if the cognitive deficits were domain-specific (within the realm of reading or numerical cognition) or domain-general (executive functions outside the realm of reading or numerical cognition) in nature; (iii) determine the nature of the relationship between math and reading deficits in the comorbid group. It was hypothesized that the deficits in the comorbid participants would either be *additive* (where the approximate sum of the deficits measured in the reading-disabled participants and the math-disabled participants), *synergistic* (an over-additivity caused by an interaction between math and reading deficits), or *antagonistic* (an under-additivity caused by an interaction between math and reading deficits). The nature of the relationship between math and reading disabilities—whether it followed the *additive deficit hypothesis* or the *synergistic deficit hypothesis, or antagonistic deficit hypothesis*—was determined using a 2x2 factorial design, where the two between-subject factors were math disability (with two levels, math disability vs. no math disability) and reading disability (also two levels, reading disability vs. no reading disability). A significant interaction between the math disability and reading disability indicates a synergistic over-additivity or an antagonistic under-additivity in the mean scores of a particular test, and lack thereof indicates an additive effect (See section 3.1, Statistical Analysis of Psychoeducational Test Scores).

Two previous studies have employed this 2x2 factorial design to identify specific cognitive deficits in comorbid dyslexia-dyscalculia. The Landerl et al. (2009) study on dyslexic-dyscalculic children and the Wilson et al. (2015) study on dyslexic-dyscalculic adults both reported that participants with comorbid dyslexia-dyscalculia exhibit domain-specific deficits in phonological processing and numerical magnitude processing, performing at a statistically-equivalent level as individuals with either dyslexia or dyscalculia alone. They reported contrasting results, however, in their participants' domain general-deficits. Wilson et al. (2015) demonstrated comorbid participants exhibited additive deficits in working memory, equivalent to the sum of the deficits in the two single-disability groups; Landerl et al. (2009) reported that the unexpected finding that both single-disability groups obtained higher working memory scores than both the comorbid disability participants and the control group. In relation to existing psychoeducational models of learning disabilities, individuals with dyslexia consistently demonstrate impaired working memory (Swanson, Howard, & Sáez, 2006; Vasic, Lohr, Steinbrink, Martin, & Wolf, 2008a; Wilson & Lesaux, 2001), but the relationship between dyscalculia and working memory is less clearly understood (Bugden & Ansari, 2015). Neither study identified a synergistic or antagonistic relationship between math disability and reading disability on any of their psychoeducational measures.

In concordance with these findings, it was hypothesized that the comorbid participants in this study would exhibit impaired reading fluency and phonological processing equivalent to those shown by individuals with reading disability alone, would exhibit impaired number sense equivalent to those shown by participants with mathematical disability alone, and would exhibit deficits in working memory equivalent to those shown by individuals with reading disability alone. Consequently, it was also hypothesized that, consistent with the proposed neuroeducational approach, it should be possible to create a mapping of correspondence between the pattern found in the psychoeducational findings and known neuroanatomical correlates, which can be empirically tested in further studies.

Method

2.1 Psychoeducational Tests

2.1.1 Tests of Achievement for Identifying Math and Reading Disabilities

The *Wide Range Achievement Test* (WRAT) is a widely-used test of basic academic skills necessary for effective learning, communication. Published in 1993, the third edition of the Wide Range Achievement test (WRAT3) consists of a three subtests: word reading, spelling, and arithmetic. In order to examine the domain-specific deficits, we examined participants' scores on the word reading and math computation subtests.

2.1.1.1 *WRAT3 Arithmetic subscale (Appendix A.1)*

The Arithmetic subscale is a test of written arithmetic problems, which included number addition, subtraction, multiplication, and problems involving fractions and decimals. Each participant one point for every correct answer. Applying the cut-off criteria used by Siegel et al. (2006), participants who scored within the 25th percentile formed the two math disability groups (MD and MDRD) in this study.

2.1.1.2 *WRAT3 Reading subscale (Appendix A.2)*

The *Reading subscale* is a single word reading test, where participants were asked to read aloud a series of increasingly difficult words. Each participant one point for every word pronounced correctly. Participants who scored within the 25th percentile formed the two reading disability groups (RD and MDRD) in this study.

2.1.2 Testing Phonological Processing

2.1.2.1 *Rosner Auditory Analysis Test (Appendix A.3)*

The Rosner Auditory Analysis test is the first of two Phoneme Deletion tasks included in this study. The test challenges the participant's phonological processing ability by prompting them to visualize a word and manipulate its phonological and morphological components (Rosner & Simon, 1971). Participants were instructed to repeat a list of 40 common English words. The test administrator would read aloud the first word on the list, and then have the participant repeat the word exactly as they heard it. Next, the test administrator asked the participant to repeat the same word without pronouncing a specific phoneme (contained in parentheses on the administrator's testing sheet), thereby "deleting" the phoneme from the word and pronouncing the word fragment(s) that remained. The administrator and the participant would repeat this back-and-forth process for each of the remaining 39 words; the level of difficulty of the words gradually increased as they progressed through the list. For the first 19 words, the participant was asked to delete the first or last phoneme of the word. In the next 13 words, the participant was asked to delete a phoneme embedded in the word, producing two fragments that formed a real English word when merged. For the last 8 words, the participant would delete a phoneme embedded in the word, producing two fragments that did not form a real English word when merged. The test administrator awarded 1 point for every correct verbal response.

2.1.2.2 *Pseudowords Phoneme Deletion task (Appendix A.4)*

This second Phoneme Deletion task tests phonological processing ability by prompting the participant to visualize a nonsensical word and manipulate its phonemic structure, without the influence of any previous experience with the word. Participants were instructed to repeat a list of 30 pseudowords (nonsensical words that follow English language phonemic rules). The test administrator would read each pseudoword as a whole, and have the participant repeat the pseudoword exactly as they heard it. Next, the test administrator asked the participant to repeat the same pseudoword without pronouncing a specific phoneme (contained in parentheses on the administrator's testing sheet), thereby "deleting" the phoneme from the pseudoword and pronouncing the word fragment(s) that remained. The administrator and the participant would repeat this back-and-forth process for each of the remaining 39 words; the level of difficulty of the words gradually increased as they progressed through the list. The test administrator awarded 1 point for every correct verbal response.

2.1.2.3 *WMRT-R Word Attack Subtest (Appendix A.5)*

Obtained from the *Woodcock Reading Mastery Tests Revised* (WRMT-R, Woodcock, 1987), the Word Attack subtest examines a participant's phoneme-grapheme awareness without relying on a verbal demonstration by the test administrator (Woodcock, 1987). Participants were instructed to read a list of 45 pseudowords one-at-a-time. The level of difficulty gradually increased throughout the test; the number of syllables in each pseudoword increased intermittently from 1 syllable to 4 or 5 syllables by the end of the list. The test administrator awarded 1 point for every correct verbal response.

2.1.3 Testing Quantitative reasoning

2.1.3.1 *KeyMath Revised Interpreting Data Subtest (See Appendix A.6)*

Participants completed the Interpreting Data subtest of the revised KeyMath Assessment (KeyMath-R). Participants were provided with a written scenario that described a real-world mathematical problem. For example: *Kareem can read sixty pages in two and one–half hours. How many pages can he read in one hour?* Each participant was provided with blank paper to formulate an answer, and were given a response pad to write their solutions. The test administrator awarded 1 point for every correct verbal response.

2.1.4 Wechsler Adult Intelligence Scale/Wechsler Intelligence Scale for Children

All participants ages 17 and over completed three subtests of the Wechsler Adult Intelligence Scale, a preeminent standardized test of intelligence and neuropsychological function (Wechsler, 1981). Participants ages 6 to 16 completed three analogous subtests from the Wechsler Intelligence Scale for Children (Wechsler, 1991).

2.1.4.1 *WAIS-R/WISC-III Vocabulary Subtest (Appendix A.7)*

The Vocabulary subtest measures a person's semantic memory retrieval. Participants performing the WAIS-R were asked to orally define a series of 30 vocabulary words, gradually increasing in difficulty. Participants performing the WISC-III were asked to name pictures representing each word. This test was included to examine the differences and similarities in reading comprehension and memory function between groups. The test administrator awarded 1 point for every correct verbal response, and recorded each participant's incorrect responses.

2.1.4.2 *WAIS-R/WISC-III Block Design subtest (Appendix A.8)*

In the Block Design subtest, participants were asked to re-create a model or a picture of a design using up to nine red and white blocks within a time limit. This test was included as a neuropsychological measure of visuospatial reasoning. The test administrator awarded 1 point for every correct verbal response.

2.1.4.3 *WAIS-R/WISC-III Digit Span subtest (Appendix A.9)*

The Digit Span subtest examines verbal working memory. Participants were presented orally with a series of single-digit numbers. In the first half of the trials, they were required to orally repeat the presented numbers in the same order they heard (forward digit span); in the second half of the trials, they were to repeat the presented numbers reverse order (backward digit span). The test administrator awarded 1 point for every correct verbal response.

2.2 Procedure

Participants were tested individually at the Psychoeducational Research and Training Centre for a three-hour session. Each testing session began with the administration of the Vocabulary, Block Design, and Digit Span subtests from the Wechsler Adult Intelligence Scale (WAIS-R) or the Wechsler Intelligence Scale for Children (WISC) for participants ages 6 – 16. Second, each participant completed the Reading, Spelling, and Arithmetic subscales of the *Wide Range Achievement Test* (WRAT3).

Next, each participant completed a series of psychoeducational tests. All participants completed four tests of phonological processing: The *Rosner Auditory Analysis task*, the *Pseudowords Phoneme Deletion task*, followed by the *Word Attack* and *Word Identification* subtests of the Woodcock Reading Mastery Tests (WRMT-R), the latter being excluded from this analysis. Lastly, participants completed the KeyMath *Interpreting Data* subtest.

Each of the 360 participants were assigned to one of four experimental groups in the 2x2 factorial design, determined by their percentile scores on the *Wide Range Achievement Test* (WRAT3). Using the cut-off criterion established by previous psychometric studies on learning disabilities (Landerl et al., 2009; Siegel, 2006; Wilson et al., 2015) participants who scored within the 25^{th} percentile on the WRAT3 Arithmetic subscale were assigned to the mathematical disability (MD) group. Likewise, participants who scored within the 25^{th} percentile on the WRAT3 Reading subscale were assigned to the reading disability (RD) group. Participants with scores within the 25th percentile on both the WRAT3 Arithmetic and Reading subscales were assigned to the comorbid MDRD group. Participants who scored above the 25^{th} percentile group on both tasks were assigned to the typical achievement (TA) control group.

2.3 Participants

The participants in this study were originally recruited for a clinical research study entitled *The Development of Reading, Language, and Memory Skills*, led by Dr. Linda Siegel in the Department of Educational Psychology and Special Education at the University of British Columbia. Data collection began in January 1997 and concluded in June 2002; this data was entered into an SPSS database and stored for future analyses. Dr. Amedeo D'Angiulli—one of the original collaborators in the study— received ownership of the database upon his appointment to the faculty of the Department of Neuroscience at Carleton University.

The purpose of the original study was to investigate the language, memory, and reading skills of normally achieving and learning disabled children and adults and to identify trends in cognitive strengths and weaknesses in a large sample population. The participants in the study were recruited from around the Greater Vancouver Area, having been referred to the Department of Educational Psychology to receive a free psychoeducational assessment. Control group participants were recruited from the graduate and undergraduate student population at UBC. Each participant completed a battery of psychoeducational and neuropsychological assessments for 3 hours (including breaks) at UBC's Psychoeducational Research and Training Centre in Vancouver. The testing format varied over the course of the 9 years of data collection, and over 50 different types of test scores were entered into database. The initial database contained 585 participants, but each participant only completed a specific subset of the tests listed. It was therefore necessary to refine the database, and to only include the participants who completed the specific psychometric tests that provide valuable information about the cognitive profiles of individuals with dyslexia and dyscalculia. A systematic procedure to refine the database was followed to select the psychometric tests and participants whose data would be included in this archival analysis (See Appendix A.10 for a full description of the test selection criteria).

The selection of test scores and participants for inclusion in this study was performed in four stages, where each stage served to filter out unwanted tests that were of no value to this archival analysis In the first stage, two tests of achievement were selected serve as diagnostic indicators for math and reading disability groups. The WRAT3 Arithmetic subscale (see Appendix, section A.1) and WRAT3 Reading subscale (Appendix section A.2) were chosen because it was completed by nearly all of the 585 participants, and these tests closely resemble the kind of psychoeducational assessments that are used in classrooms.

In the second stage, three specific domains of cognitive function were identified for inclusion in this study: domain-specific tests that examine phonological processing (the reading domain) or numerical magnitude processing (the mathematical domain), and domain-general tests that examine executive functions (such as working memory and spatial reasoning). Three tests in the reading domain were selected for inclusion: the Rosner Auditory Analysis task, Pseudowords Phoneme Deletion task, and the WRMT Word Attack subtest (see Appendix, sections A.3, A.4, A.5., respectively). Each of these three tests examine a person's ability to verbally decode words and pseudowords, and are thereby considered to be valid tests of phonological processing. In the mathematical domain, only one test was selected: the Interpreting Data subtest of the revised KeyMath Assessment (see Methods, section 2.1.2.3 for a full description). The database did not contain any tests similar to the symbolic or nonsymbolic numerical comparison or number line tasks (as described in Introduction, section 1.3.1); the KeyMath Interpreting Data subtest was selected because it was the only math-related test that was also administered to the participants who completed the Rosner, Pseudowords, and Word Attack tasks. The Interpreting Data subtest is a test of quantitative reasoning with word problems, and is not considered to be a valid test of numerical magnitude processing or the approximate number system—a key limitation of this study (see Discussion, section 4.2). Three neuropsychological tasks that test domain-general cognitive functions were selected: The Vocabulary, Block Design, and Digit Span subtests of the WAIS-R (for participants ages 17 and older) or the WISC-III (participants ages 16 and younger).

The third and final stage in refining the database involved selectively omitting participants whose data were deemed to be ineligible for the present analysis. 53 participants were excluded due to incomplete data entry—some of the test scores for these participants were found in the database, while other scores were missing. In addition 49 participants were excluded because their estimated IQ score was below 70. 113 Participants were excluded due to differences in testing format; they did not complete all nine of the tests named above that were required for inclusion in this analysis.

The 25^{th} percentile cut-off criterion for the WRAT3 Arithmetic and Reading subtests produced four experimental groups: the math disability (MD) group (participants who scored 25^{th} percentile or lower on the WRAT3 Arithmetic subscale), the reading disability (RD) group (25^{th} percentile or lower on the WRAT3 Arithmetic subscale), the comorbid math and reading disability (MDRD) group (25^{th} percentile or lower on both WRAT3 subscales), and the typical achievement (TA) control group (higher than the 25^{th} percentile on both WRAT3 subscales). The mean percentile scores for each group are reported in Table 1; differences in performance were evaluated using a one-way ANOVA and Tukey post-hoc multiple comparisons. For the WRAT3 Arithmetic subtest, significant differences were observed between the TA and MD groups ($p < 0.01$) and the TA and MDRD groups ($p < 0.01$); the TA and RD groups performed at a statistically equivalent level ($p = 0.184$), as did the MD and MDRD groups performed ($p = 0.627$). The opposite result was shown in the multiple comparisons for the WRAT3 Reading subtest; significant differences were observed between the TA and RD groups ($p < 0.01$), and between the TA and MDRD groups ($p < 0.01$); whereas the TA and MD groups performed at a statistically equivalent level ($p = 0.495$), as did the RD and MDRD groups ($p = 0.903$).

The average age of the participants (on the day of testing) in each experimental group are presented in Table 1. A one-way ANOVA followed by Tukey post-hoc multiple comparisons revealed that the average age of the RD group participants was significantly lower than the average age of the TA group ($p = 0.008$), the MD group ($p = 0.017$) and the MDRD group ($p = 0.007$). A two-way MANCOVA was conducted to examine the effect of age on the scores from all seven psychoeducational tests, with math disability and reading disability as the independent variables and age as a covariate. Using the Bonferroni procedure to correct for multiple ANOVAs (with a significant threshold of $p < 0.008$), there were no significant interactions between age and math disability, nor between age and reading disability, on the mean scores for any of the psychoeducational tests (Wilks' Lambda = 0.012). Furthermore, a three-way MANOVA was conducted with math disability, reading disability, and age category as independent variables. The participants were divided into two age categories: below age 16 and above age 16. MD x Age Category interaction was not significant (Wilks' Lambda = 0.780) nor was the RD x Age Category interaction Wilks' Lambda = 0.349). As a result, the low average age of the dyslexic did not appear to have a significant effect on the psychoeducational test results as whole.

Estimated IQ scores were calculated using the sum of the WAIS-R Vocabulary subtest and the WAIS-R Block Design subtest (Sattler & Hoge, 2006). This was the only method available for these participants; a Full Scale IQ test was not administered as a part of the testing procedure. The researchers acknowledge that this is not the recommended method for identifying low IQ, nor does it take the place of a Full IQ score report (Ryan et al., 1988; Wagner et al., 2010). None of the participants included in this analysis obtained estimated IQ scores below 70, which is the clinical threshold for low IQ (Deb, Thomas, & Bright, 2001).

Three measures of socioeconomic status (SES)—education, occupation, and median income—were evaluated in the presented study, and are presented at the bottom of Table 1. Using Kuppuswamy's modified socioeconomic scale to measure SES in urban communities (Bairwa, Rajput, & Sachdeva, 2013), each participant received a numerical rating between 1 and 7 for the highest level of education they had achieved by the day of testing (1 = elementary school certificate or currently enrolled, 2 = middle school certificate, 3 = secondary school diploma, 4 = some college/university or post-secondary diploma, 5 = college/university degree, 6 = graduate degree, 7 = professional degree). Each participant received an individual rating for their occupation status (1 = unemployed, 2 = unskilled worker, 3 = semi-skilled worker, 4 = skilled worker, 5 = clerical, shop-owner, farmer, 6 = semi-profession, 7 = profession). For the participants ages 16 and younger, the highest level of occupation status achieved by either one of their parents was used as a proxy for their own occupation rating. Median household income ratings were generated for each participant by the postal code of the home address that they provided on the day of testing (1 = $50,000 or less, 2 = $50,000 - $60,000, 3 = $60,000 - $70,000, 4 = $70,000 - $80,000, 5 = $80,000 - $90,000, 6 = $90,000 or more), based on census figures from 2005 (Cain, 2013). One-way ANOVAs and Tukey post-hoc multiple comparisons were conducted to identify any between-group differences in the three SES measures. There was a significant difference in mean education rating between the TA and RD groups ($p = 0.007$); this can be explained by the lower average age of the RD group in the present study, as previously stated. There were no significant between-group differences in occupation or median income rating.

Table 1

Characteristics of the four experimental groups

	Control	*MD*	*RD*	*MDRD*	*All groups*
n	158	69	46	87	*360*
Mean age (years)	26.47 (14.66)	26.80 (12.69)	19.22 (10.96)	27.22 (12.99)	*25.79 (13.65)*
n Female	77	35	16	47	*175*
% Female	48.73%	50.72%	34.78%	54.02%	*48.61%*
WRAT3 Arithmetic Mean Score	57.82 (19.38)	<u>13.62</u> (7.34)	50.26 (17.05)	<u>10.34</u> (7.66)	*36.84 (26.81)*
WRAT3 Reading Mean Score	63.42 (19.24)	53.00 (17.18)	<u>12.09</u> (8.20)	<u>10.14</u> (8.11)	*41.99 (28.77)*
Estimated IQ	109.61 (14.28)	97.75 (13.45)	100.80 (16.42)	88.74 (13.57)	*101.17 (16.51)*
Education Rating	3.23 (1.41)	3.10 (1.29)	2.43 (1.19)	3.15 (1.22)	*3.08 (1.31)*
Occupation Rating	3.65 (1.30)	3.69 (1.53)	3.67 (0.87)	3.20 (1.44)	*3.54 (1.37)*
Median Income Rating	3.52 (1.63)	3.41 (1.36)	3.50 (1.34)	3.49 (1.28)	*3.49 (1.48)*

Note. Numbers in parentheses represent one standard deviation from the mean. Underlined numbers are mean percentile scores that are within the 25th percentile on the WRAT3 Arithmetic or WRAT3 Reading subtest.

2.4 Systematic Review of the Neuroanatomical Correlates of Dyslexia-Dyscalculia Comorbidity

The cognitive deficits of individuals with comorbid dyslexia-dyscalculia were mapped to their associated neuroanatomical substrates using evidence from existing research on the functional and structural correlates of dyslexia and dyscalculia. The protocol for this review followed the guidelines established by the *Preferred Reporting Items for systematic Review and Meta-Analysis Protocols* (Moher et al., 2015); a detailed checklist with inclusion/exclusion criteria, search terms, and methods is presented in Table 2.

The systematic review was performed in three stages. The first stage was a preliminary search to identify well-cited authors on math and reading disabilities and the avenues for future research. The second stage of literature review provided working definitions of dyslexia and dyscalculia. The third and most crucial stage served to identify (i) the neural correlates unique to dyslexia, (ii) the neural correlates unique to dyscalculia, (iii) the neural correlates that are shared between the disorders. Using PubMed to access the MEDLINE database operated by the National Institutes of Health, a detailed search of biomedical literature was performed to identify functional neuroimaging to analyze physiological changes during phonological or nonsymbolic magnitude comparison tasks, or structural neuroimaging to examine differences in white and/or grey matter tractography in people with dyslexia and dyscalculia. In order to support the model with direct neuropsychological evidence, a second detailed search of medical literature was performed using PubMed to identify empirical studies that examined patients with *alexia* (acquired dyslexia) or *acalculia* (acquired dyscalculia), who had suffered damage to structures that mediate in math or reading ability, caused by an ischemic stroke or brain tumor. The results are presented in Table 5.

Table 2

PRISMA-P Protocol for Systematic Review (Moher et al., 2015)

Rationale	To identify any neuroanatomical structures whose atypical function may be associated with the cognitive deficits exhibited by individuals with dyslexia and dyscalculia.
Objectives	The review answered the following questions: • "What brain regions show atypical activity in dyslexia alone?" • "What brain regions are show atypical activity in dyscalculia alone?" • "What brain regions are atypical activity in comorbid dyslexia-dyscalculia?
Eligibility Criteria	• Studies published in academic research journals since January 1, 2004. This marks the beginning of the current definition of specific learning disability (Turnbull, Huerta, & Stowe, 2004). • The studies involved 20+ participants, males and females ages 6 and older. • The studies followed a quasi-experimental design with *at least* two groups: one group with a learning disability (dyslexia or dyscalculia) and a control group. • The studies did not involve individuals with any medical condition (other than dyslexia or dyscalculia) or any other life circumstance that could have influenced their performance on the cognitive tasks (ADHD, neurodegenerative disease, lack of education, etc.). • The investigators applied one of the three following techniques:

	a) Functional magnetic resonance imaging (fMRI) to examine physiological correlates of cognitive activity during phonological or numerical magnitude comparison tasks b) Diffusion tensor imaging (DTI) to examine structural differences in white or grey matter composition between key neurological structures c) Lesion-symptom mapping (caused by either a stroke or a brain tumor)
Information Sources	• Google Scholar • American Psychological Association (PsycINFO) • Education Resources Information Center (ERIC) • NIH MEDLINE Database (PubMed)
Search Strategy	Step 1: Preliminary Search A preliminary search was performed using Google Scholar to find the leading authors in learning disabilities research, identify their seminal publications on dyslexia, dyscalculia, and provide a working definition for each disorder. Step 2: Existing Meta-Analyses A secondary search was performed to using PsycINFO and ERIC to identify studies that examined comorbid dyslexia-dyscalculia, and to identify any existing meta-analyses on the cognitive or neurological correlates of each learning disability. Step 3: Detailed Search A detailed search of medical literature was performed using PubMed to identify empirical studies that used functional or structural MRI to examine individuals with (a) dyscalculia and (b) dyslexia, and that report the neuroanatomical

structures whose atypical function or white matter composition is associated with each disorder.

a) A combination of the following search terms were used to identify functional and structural neuroimaging studies on dyslexia: “neurobiological dyslexia” “neurobiological reading disability” “brain region dyslexia” “brain region reading disability” “neuroimaging dyslexia” “neuroimaging reading disability” “fMRI dyslexia” “fMRI reading disability”

b) A combination of the following search terms were used to identify functional and structural neuroimaging studies on dyscalculia: “neurobiological dyscalculia” “neurobiological math disability” “brain region dyscalculia” “brain region math disability” “neuroimaging dyscalculia” “neuroimaging math disability” “fMRI dyscalculia” “fMRI math disability”

Step 4: Lesion-symptom Mapping Studies

A second detailed search of medical literature was performed using PubMed to identify empirical studies that examined patients with *alexia* (acquired dyslexia) or *acalculia* (acquired dyscalculia), who had suffered damage to structures that mediate in math or reading ability, caused by an ischemic stroke or brain tumor.

a) A combination of the following search terms were used to identify lesion-symptom case studies of patients with alexia: “neurobiology AND acquired dyslexia” “neurobiology AND alexia” “lesion AND acquired dyslexia” “lesion AND alexia” “stroke AND acquired dyslexia” “stroke AND alexia” “brain tumor AND acquired dyslexia” “brain tumor AND alexia”.

	b) A combination of the following search terms for acquired dyscalculia: “neurobiology AND acquired dyscalculia” “neurobiology AND acalculia” “lesion AND acquired dyscalculia” “lesion AND acalculia” “stroke AND acquired dyscalculia” “stroke AND acalculia” “brain tumor AND acquired dyscalculia” “brain tumor AND acalculia”.
Study Records	One independent reviewer will select the published studies that fit the eligibility criteria. The selected publications will be legally stored and classified using *Mendeley Desktop* (Version 1.15.2) for Windows 10.
Outcomes & Prioritization	The desired outcome will be a list of brain regions that are involved in dyslexia and dyscalculia. Priority will be given to studies that included participants all four groups (participants with dyslexia, dyscalculia, comorbid dyslexia-dyscalculia, and controls).
Synthesis	The results of the systematic review will be synthesized using a table as displayed below. Each brain region identified in the review will be classified by learning disability (whether the region is associated with dyslexia, dyscalculia), as well as by the type of atypical functionality displayed (whether the brain region is generally more active or inactive in individuals with the learning disability). Of primary interest are the neuroanatomical structures whose atypical function is common to dyslexia and dyscalculia; these structures will be underlined in the table.

Results

3.1 Statistical Analysis of Psychoeducational Test Scores

In order to examine relationship between math disability, reading disability, and each group's performance on the psychoeducational tests, two approaches to statistical analysis were employed. First, a two-way analysis of variance (ANOVA) was conducted for each of the seven psychoeducational tests, to test for the significance of an interaction between math disability and reading disability. Second, a one-way ANOVA was performed on each psychoeducational test, to identify any statistically significant differences between the mean scores of the four experimental groups.

The two-way ANOVAs followed a 2x2 factorial design, where the two between-subject factors were math disability (with two levels, math disability vs. no math disability) and reading disability (also two levels, reading disability vs. no reading disability), the same the procedure used in previous studies on individuals with comorbid math and reading disabilities (Landerl et al., 2009; Wilson et al., 2015). For these ANOVAs, the interaction term serves as an indicator of the type of relationship between deficits in individuals with MDRD. For any of the seven psychoeducational tests, a significant interaction between math disability and reading disability would indicate a synergistic or antagonistic relationship between math and reading disability—an over-additivity or under-additivity of deficits in domain-specific or domain-general cognitive processes. Under-additivity would suggest that there is a common, overlapping cognitive deficit between individuals with MD and those with RD; over-additivity would suggest that the relationship is associated with a specific domain-general deficit, or group of deficits that are not influenced by math or reading deficits alone.

After determining the presence or absence of a significant interaction, one-way ANOVAs were used to analyze between-group differences in performance, where the dependent variable was the psychoeducational test score, and the independent variables were the learning disability group. Post-hoc tests were conducted for each one-way ANOVA using the Tukey multiple comparison procedure, in order to identify any significant differences between mean scores for any two learning disability groups. With four independent variables, a total of six multiple comparisons were of interest (TA vs. MD, TA vs. RD, TA vs. MDRD, MD vs. RD, MD vs. MDRD, and RD vs. MDRD).

The two-way analysis are presented with description of statistical significance, F-values, p-values, and partial η^2 values. For the one-way analysis, the overall observed pattern with mean scores ± standard deviations for each group are presented first, followed by the tests of linear contrasts. The mean difference between each group's average scores confidence intervals and p-values from the Tukey post-hoc multiple comparisons are presented last. All analyses were performed using SPSS 22.0 for Windows 10 with a significance threshold of $p < 0.05$. Table 3 presents a summary of the psychoeducational test scores for each of the four experimental groups.

Table 3

Summary of the psychoeducational test scores for each experimental group

Construct Tested	Test	TA	MD	RD	MDRD	Contrast Pattern[a]
Phonological processing	Auditory Analysis	31.77	29.94	23.47	21.29	TA = MD > RD = MDRD
	Pseudowords	22.06	21.17	15.93	12.17	TA = MD > RD > MDRD
	Word Attack	32.79	33.24	20.15	20.24	TA = MD > RD = MDRD
Quantitative reasoning	Interpreting Data	11.75	9.60	8.46	7.21	TA > MD = RD = MDRD
Semantic memory	Vocabulary	11.75	9.60	8.45	7.21	TA > MD = RD > MDRD
Visuospatial reasoning	Block Design	11.47	8.98	11.65	8.59	TA = RD > MD = MDRD
Working memory	Digit Span	10.30	8.65	9.00	6.77	TA > RD = MD > MDRD

Note. In the statistical trend column, the symbol " > " indicates a significant difference at $p < 0.05$, whereas the symbol " = " indicates a lack of significant difference at $p < 0.05$. [a] Patterns identified by Tukey post-hoc tests. The MD x RD interactions were nonsignificant for all tests ($p > 0.05$).

3.1.1 Tests of Phonological Processing

Mean scores on the three tests of phonological processing are shown in Figures 3, 4, and 5. For the Rosner Auditory analysis task, mean scores (± 1 SD) decreased in order from the TA group (31.77 ± 8.56) to the MD group (29.94 ± 8.93), to the RD group (23.48 ± 9.52), and lastly the MDRD group (21.30 ± 10.31). For the Pseudowords task, the TA group obtained the highest scores (22.09 ± 7.39), followed by the MD group (21.17 ± 6.93), the RD group (15.93 ± 7.06), and finally the MDRD group (12.25 ± 7.37). For the Word Attack Task, this time the MD group obtained the highest scores (33.25 ± 8.17), followed closely by the TA group (32.80 ± 7.39), then the MDRD group (20.24 ± 10.50), and the RD group (20.15 ± 10.24).

The results of the two-way ANOVA did not reveal a significant interaction between math disability and reading disability for the Auditory Analysis task ($F(0.95, 1, 356) = 0.05$, MSE = 4.21, $p = 0.82$, $\eta_p^2 < 0.01$), the Pseudowords task ($F(0.95, 1, 356) = 2.89$, MSE = 151.60, p = 0.09 , $\eta_p^2 = 0.01$), nor the Work Attack task ($F(0.95, 1, 356) = 0.04$, MSE = 3.73, $p = 0.84$, $\eta_p^2 <$ 0.01). The analysis of simple main effects revealed a significant main effect of reading disability for all three tests of phonological processing; the reading-disabled participants obtained significantly lower mean scores on the Auditory Analysis task ($F(0.95, 1, 356) = 63.89$, MSE = 5388.00, $p < 0.01$, $\eta_p^2 = 0.15$), the Pseudowords task ($F(0.95, 1, 356) = 80.500$, MSE = 4229.71, $p < 0.01$, $\eta_p^2 = 0.18$), and the Work Attack task ($F(0.95, 1, 356) = 0.042$, MSE =12122.51, $p <$ 0.01, $\eta_p^2 = 0.27$). There was a significant main effect of math disability for the Pseudowords task ($F(0.95, 1, 356) = 7.62$, MSE = 400.28, $p = 0.01$, $\eta_p^2 = 0.02$).

The one-way ANOVA identified a significant effect of learning disability group on the mean scores of the Auditory Analysis task ($F(0.95, 3, 356) = 28.90$, MSE = 2448.46, p < 0.01, $\eta_p^2 = 0.196$), the Pseudowords task ($F(0.95, 3, 356) = 39.28$, MSE = 2067.86, $p < 0.01$, η_p^2 = 0.25), and the Work Attack task ($F(0.95, 3, 356) = 49.92$, MSE = 4528.74, $p < 0.01$, $\eta_p^2 = 0.30$). For the Auditory Analysis task, Tukey post-hoc multiple comparisons indicated that the mean score difference between the TA and RD groups was significant (8.29, 95% *CI* (4.31 to 12.27), p < 0.01), as was the mean difference between the TA and MDRD groups (7.30, 95% *CI* (7.30 to 13.64), $p < 0.01$). On the Pseudowords task, post-hoc tests indicated that the mean difference between TA and RD groups' scores was significant (6.15, 95% *CI* (3.02 to 9.29), $p < 0.01$), as was the mean difference between the TA and MDRD groups (9.84, 95% *CI* (7.34 to 12.43), p < 0.01). For the Word Attack Task, the mean difference between the TA and RD groups' scores was significant (12.65, 95% CI (8.53 to 16.76), p < 0.01), as was the mean difference between TA and MDRD (12.56, 95% CI (9.27 to 15.84), p < 0.01).

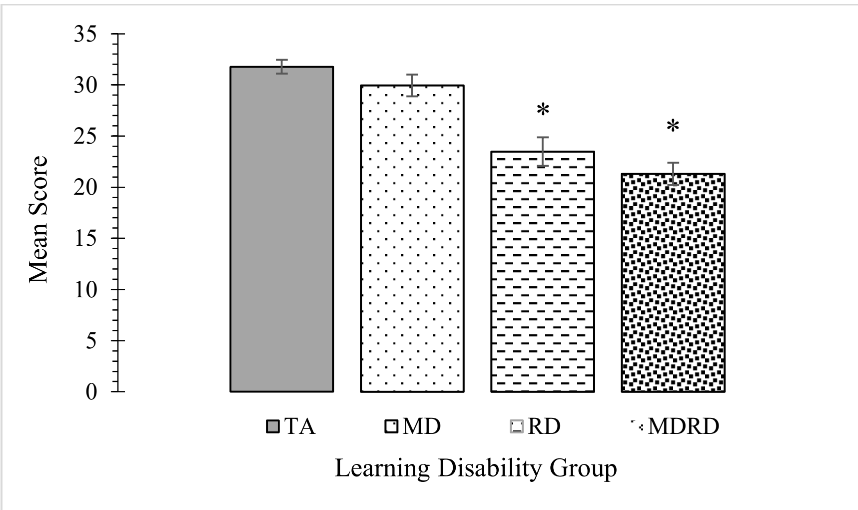


Figure 3. Mean scores for the Rosner Auditory Analysis task. The symbol * indicates significant difference from the typical achievement (TA) control group at $p < 0.05$. Bars represent one standard error.

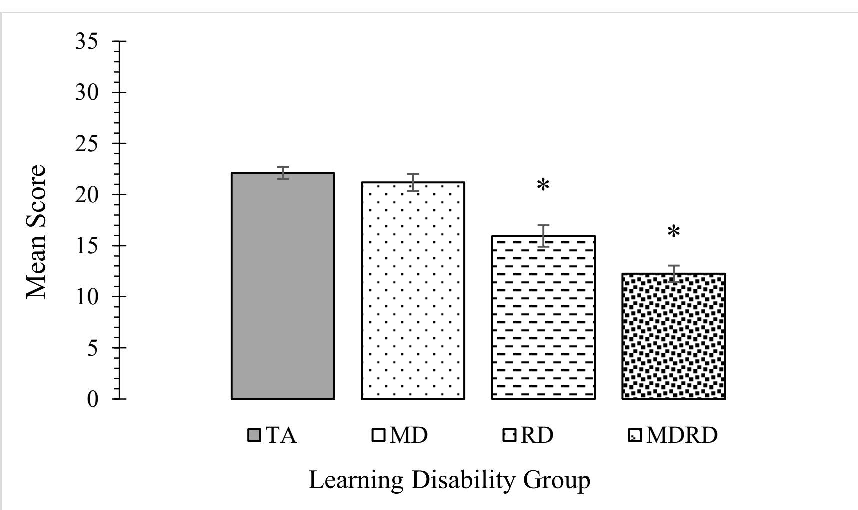


Figure 4. Mean scores for the Pseudowords Phoneme Deletion task. The symbol * indicates a significant difference from the typical achievement (TA) control group at $p < 0.05$. The symbol ** indicates a significant difference from the reading disability (RD) group at $p < 0.05$. Bars represent one standard error.

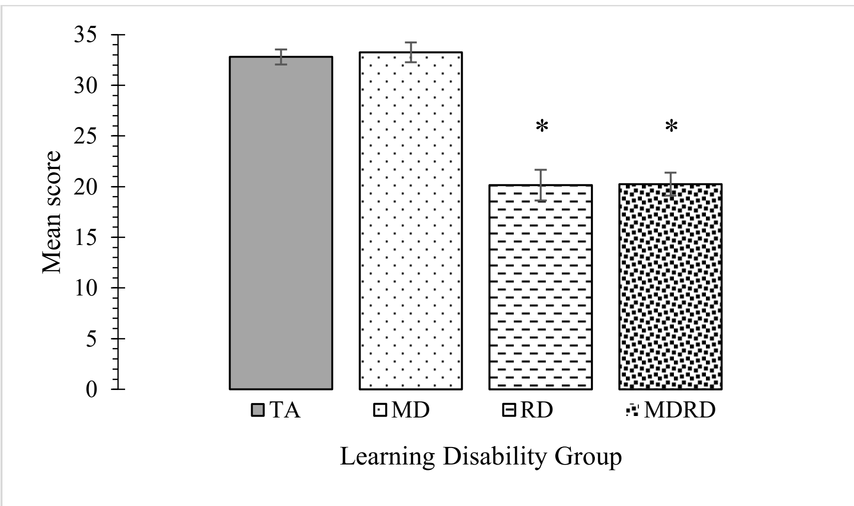


Figure 5. Mean scores for the WRMT-R Word Attack subtest. The symbol * indicates significant difference from the typical achievement (TA) control group at $p < 0.05$. Bars represent one standard error.

3.1.2 The KeyMath Interpreting Data Subtest

Mean scores and standard errors for the KeyMath Interpreting Data subtest are shown in Figure 6. The TA group obtained the highest mean scores (13.75 ± 4.14), followed by the MD group (12.03 ± 4.28), the RD group (11.59 ± 10.28), and finally the MDRD group (10.28 ± 4.77).

The two-way ANOVA did not reveal a significant interaction between math disability and reading disability (F(0.95, 1, 356) = 0.12, MSE = 2.389, p = 0.73, η_p^2 = 0.01). There was a significant main effect of math disability ($F(0.95, 1, 356) = 9.08$, $MSE = 176.53$, $p < 0.01$, $\eta_p^2 = 0.03$), as well as a significant main effect of reading disability ($F(0.95, 1, 356) = 15.01$, $MSE = 291.92$, $p < 0.01$, $\eta_p^2 = 0.04$).

The one-way ANOVA identified a significant effect of learning disability group on the level of performance ($F(0.95, 3,356) = 12.23$, $MSE = 238.550$, $p < 0.01$, $\eta_p^2 = 0.093$). Tukey post-hoc multiple comparisons revealed that the mean scores of the TA group were significantly higher than the MD group (1.72, 95% *CI* (0.07 to 3.36), $p = 0.04$), the RD group (2.16, 95% *CI* (0.25 to 4.07), $p = 0.02$) and the MDRD group (3.47, 95% *CI* (1.95 to 4.99), $p < 0.01$). There were no significant differences between the mean scores of the MD and MDRD groups (1.75, 95% *CI* -0.08 to 3.59), $p = 0.07$), between the RD and MDRD groups (1.31, 95% *CI* -0.77 to 3.39), $p = 0.36$), or between the MD and RD groups (0.44, 95% *CI* (-1.73 to 2.61), $p = 0.95$).

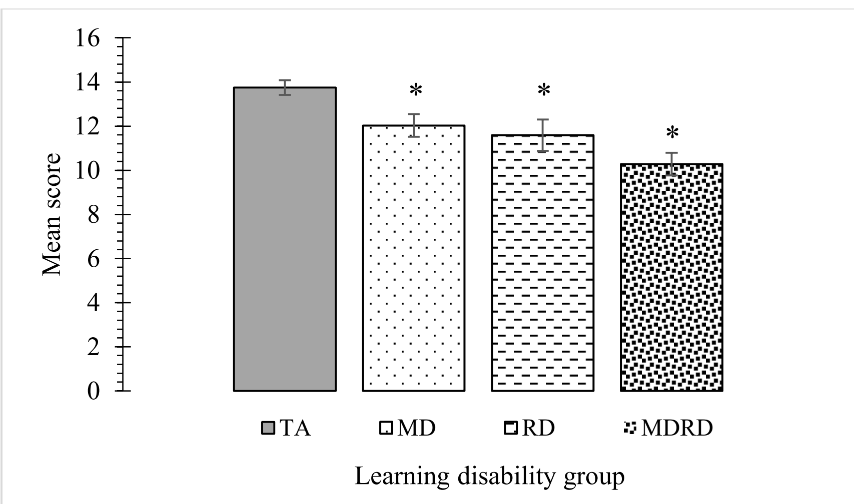


Figure 6. Mean scores for the KeyMath Interpreting Data subtest. The symbol * indicates significant difference from the typical achievement (TA) control group at $p < 0.05$. Bars represent one standard error.

3.1.3 The Wechsler Intelligence Scale Subtests

Mean scores on the three tests of phonological processing are shown in Figures 7, 8, and 9. For the WAIS-R Vocabulary subtest, mean scores (± 1 SD) decreased in order from the TA group (11.56 ± 2.69) to the MD (9.61 ± 2.47) and RD groups (8.46 ± 3.79), and lastly the MDRD group (7.22 ± 2.47). The results of the WAIS-R Digit Span task revealed a similar pattern; the TA group obtained the highest mean scores (10.34 ± 2.69), followed by the RD (8.98 ± 2.55) and MD groups (8.65 ± 2.56), and then the MDRD group (6.77 ± 2.14). For the WAIS-R Block Design subtest, this time the RD group obtained the highest mean scores (11.65 ± 3.47), then the TA group (11.49 ± 2.93), the MD group (8.99 ± 2.97), and finally the MDRD group (8.60 ± 3.11).

The two-way ANOVA did not reveal a significant interaction on the Vocabulary subtest ($F(0.95, 1, 356) = 1.33$, $MSE = 13.78$, $p = 0.25$, $\eta_p^2 < 0.01$), nor on the Block Design subtest ($F(0.95, 1, 356) = 0.68$, $MSE = 6.291$, $p = 0.41$, $\eta_p^2 = 0.02$), nor on the Digit Span subtest ($F(0.95, 1, 356) = 0.93$, $MSE = 5.89$, $p = 0.34$, $\eta_p^2 < 0.01$). There was a significant main effect of math disability on the mean scores of the Vocabulary subtest ($F(0.95, 1, 356) = 20.92$, $MSE = 217.03$, $p < 0.01$, $\eta_p^2 = 0.06$), the Block Design subtest ($F(0.95, 1, 356) = 61.83$, $MSE = 575.26$, $p < 0.01$, $\eta_p^2 = 0.15$), and the Digit span subtest ($F(0.95, 1, 356) = 44.84$, $MSE = 284.77$, $p < 0.01$, $\eta_p^2 = 0.11$). There was significant main effect of reading disability on the mean scores of the Vocabulary ($F(0.95, 1, 356) = 58.490$, $MSE = 606.87$, $p < 0.01$, $\eta_p^2 = 0.14$) and the Digit span subtest ($F(0.95, 1, 356) = 31.18$, $MSE = 198.04$, $p < 0.01$, $\eta_p^2 = 0.08$), but was not significant for the Block Design subtest ($F(0.95, 1, 356) = 0.12$, $MSE = 1.13$, p = 0.73, $\eta_p^2 < 0.01$).

The one-way ANOVA identified a significant effect of learning disability group on the mean scores of the Vocabulary subtest ($F(0.95, 3,356) = 50.14$, $MSE = 383.92$, $p < 0.01$, $\eta_p^2 =$

0.30), the Block Design subtest (F(0.95, 3,356) = 24.23, MSE = 225.95, $p < 0.01$, $\eta_p^2 = 0.17$), and the Digit Span subtest (F(0.95, 3,356) = 37.75, MSE = 240.86, $p < 0.01$, $\eta_p^2 = 0.24$). For the Vocabulary subtest, post-hoc tests showed that the mean difference between the TA and MD groups' scores was significant (1.95, 95% *CI* (-0.92 to 2.98), $p < 0.01$), as was the mean difference between TA and RD (3.10, 95% *CI* (1.90 to 4.30), $p < 0.01$) and the TA and MDRD groups' scores (4.34, 95% *CI* (3.39 to 5.29), $p < 0.01$). The mean difference between MD and MDRD was also significant (2.39, 95% *CI* (2.39 to 3.54), $p < 0.01$). For the Block Design subtest, the mean difference between the TA and MD (2.50, 95% *CI* (1.36 to 3.64), $p < 0.01$) and the TA and MDRD groups' scores was significant (2.89, 95% *CI* (1.84 to 3.94), $p < 0.01$). On the Digit Span subtest, the mean difference between the TA and MD groups (1.68, 95% *CI* (0.74 to 2.62), $p < 0.01$), the TA and RD groups (1.36, 95% *CI* (0.26 to 2.45), $p = 0.01$), and the TA and MDRD groups (3.57, 95% *CI* (2.69 to 4.44), $p < 0.01$) were all statistically significant. The mean difference between MD and MDRD was also significant (1.88, 95% *CI* (0.83 to 2.93), $p < 0.01$), as was the difference between RD and MDRD (2.21, 95% *CI* (1.02 to 3.40), $p < 0.01$).

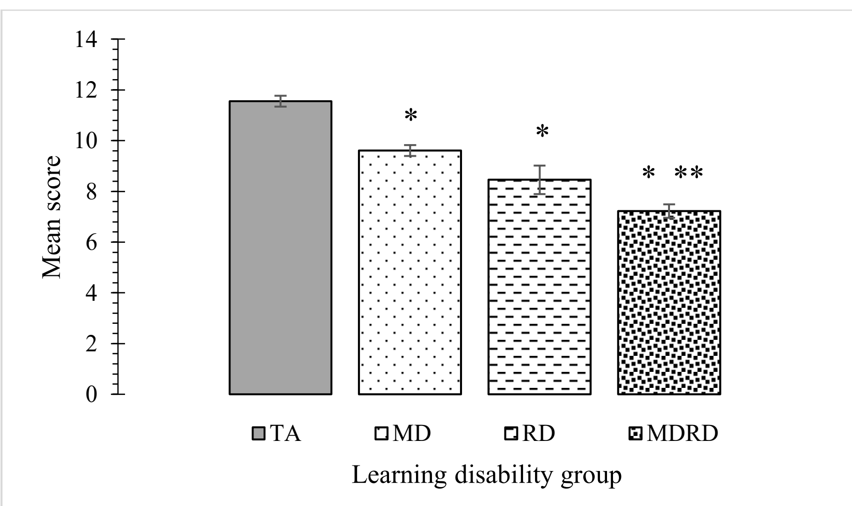


Figure 7. Mean scores for the WAIS-R Vocabulary subtest. The symbol * indicates significant difference from the typical achievement (TA) control group at $p < 0.05$. The symbol ** indicates

significant difference from the mathematical disability (MD) group at $p < 0.05$. Bars represent one standard error.

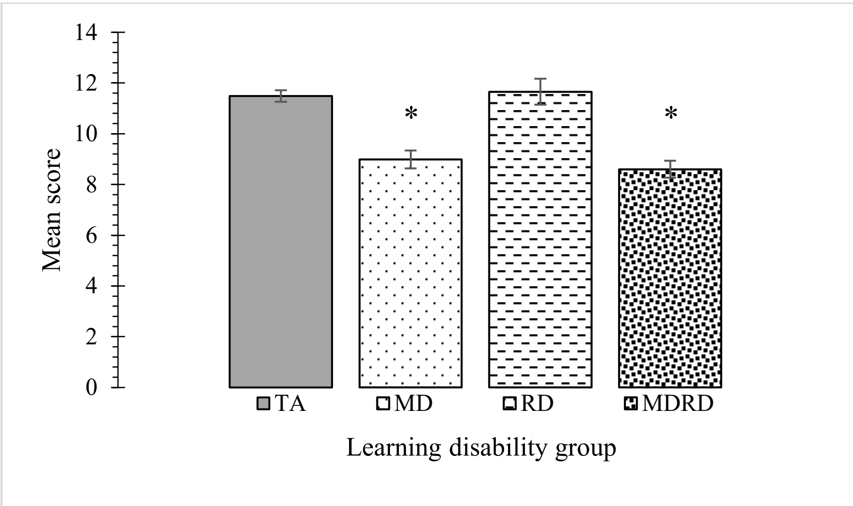


Figure 8. Mean scores for the WAIS-R Block Design subtest. The symbol * indicates significant difference from the typical achievement (TA) control group at $p < 0.05$. Bars represent one standard error.

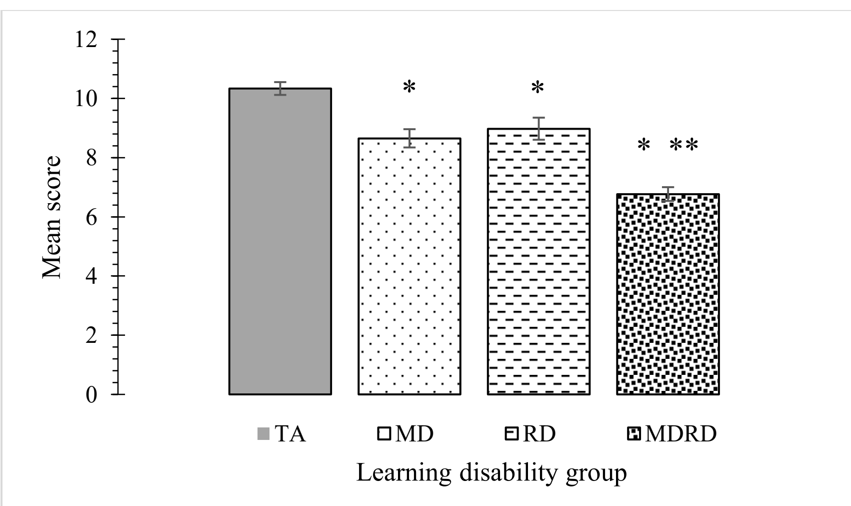


Figure 9. Mean scores for the WAIS-R Digit Span subtest. The symbol * indicates significant difference from the typical achievement (TA) control group at $p < 0.05$. The symbol ** indicates significant difference from the mathematical disability (MD) group at $p < 0.05$. The symbol ***

indicates significant difference from the reading disability (RD) group at $p < 0.05$. Bars represent one standard error.

3.1.4 The Cognitive Profiles of mathematical disability, reading disability, and comorbid math and reading disability

Table 4 presents a summary of the cognitive profiles of MD, RD, and MDRD participants in this study, organized by their psychoeducational domain. In the reading domain, the two reading-disabled groups demonstrated impaired phonological processing as reflected by their performance on the three corresponding psychoeducational tests. Similarly, in the math domain, the two math-disabled groups demonstrated impaired quantitative reasoning on the KeyMath Interpreting Data subtest. However, unexpectedly, the RD group also demonstrated a deficit in quantitative reasoning, equal in magnitude to the two math-disabled groups. In the domain-general tests, the MD and RD groups demonstrated impaired verbal semantic memory and working memory; the MD group also demonstrated impaired visuospatial reasoning. Meanwhile, the MDRD group demonstrated additional impairments to their verbal semantic memory and working memory.

Table 4

The cognitive profiles of the MD, RD, and MDRD participants.

Domain	MD Group	RD group	MDRD group
Reading	N/A	Impaired phonological processing	Impaired phonological processing
Math	Impaired quantitative reasoning	Impaired quantitative reasoning*	Impaired quantitative reasoning
Domain-general	Impaired verbal semantic memory Impaired verbal working memory Impaired visuospatial reasoning	Impaired verbal semantic memory Impaired verbal working memory	Impaired verbal semantic memory + Impaired verbal working memory + Impaired visuospatial reasoning

Note. The symbol * indicates an unexpected finding. The symbol + indicates an additive deficit, where the MDRD group demonstrated a significantly greater deficit than either the MD or RD group.

3.2 Systematic Review Report: Mapping reading and mathematical disability deficits to neuroanatomical correlates of dyslexia & dyscalculia

Table 5 summarizes the neuroanatomical correlates of dyslexia and dyscalculia. This review includes studies publishes since 2004 used either (a) functional neuroimaging to examine the cerebral blood oxygenation in individuals with dyslexia and dyscalculia, who performed during phonological or numerical magnitude tasks; (b) structural neuroimaging to examine white or grey matter tractography in individuals with dyslexia or dyscalculia; (c) lesion-symptom mapping in individuals who suddenly developed alexia (acquired dyslexia) or acalculia (acquired dyscalculia) after suffering a stroke or recovering from surgery to remove a brain tumor.

Table 5

Systematic review of the neuroanatomical correlates of dyslexia and dyscalculia

Method	Neuroanatomical correlates of Dyslexia	Neuroanatomical correlates of Dyscalculia
Functional (fMRI, PET)	Hypoactivation during phonological tasks: • L inferior frontal gyrus (Booth et al., 2007; Brambati et al., 2006; Cao et al.,, 2006) • L superior temporal gyrus (Brambati et al., 2006; Kronbichler et al., 2006b; Meyler et al., 2007) • L superior temporal sulcus (Brambati et al., 2006; Cao et al., 2006; Meyler et al., 2007) • L middle temporal gyrus (Grunling et al., 2004) • L inferior temporal gyrus (Cao et al., 2006; Kronbichler et al., 2006b; McCrory et al., 2005) • L fusiform gyrus (Kronbichler et al., 2008; McCrory et al., 2005) • L angular gyrus (Hoeft et al., 2006; Kronbichler et al., 2006b; Meyler et al., 2007; Schulz et al., 2008) Hyperactivation phonological tasks: • R medial prefrontal cortex (Grunling et al., 2004) • L primary motor cortex (Grunling et al., 2004; Kronbichler et al., 2006b) • L anterior insula (Grunling et al., 2004; Kronbichler et al., 2006b; Meyler et al., 2007) • L caudate nuclei (Kronbichler et al., 2006a; Meyler et al., 2007)	Hypoactivation during numerical magnitude tasks: • L superior frontal gyrus (Kaufmann et al., 2009a) • L medial prefrontal cortex (Price et al., 2007) • R fusiform gyrus (Kaufmann et al., 2009a; Price et al., 2007) • R intraparietal sulcus (IPS) alone (Price et al., 2007) • L & R intraparietal sulci (Kaufmann et al., 2009a; Kucian et al., 2006; Mussolin et al., 2010) Hyperactivation during numerical magnitude tasks: • R superior frontal gyrus (Kaufmann et al., 2009a) • L postcentral gyrus (Kaufmann et al., 2009a) • L & R supramarginal gyrus (Kaufmann et al., 2009a) • L angular gyrus (Kaufmann et al., 2009a; Kucian et al., 2006)

Structural (MRI, DTI)	Lower grey matter volume vs. controls • L inferior frontal gyrus (Kronbichler et al., 2008) • R middle frontal gyrus (Krafnick, et al., 2014) • L inferior temporal gyrus (Kronbichler et al., 2008) • L fusiform gyrus (Kronbichler et al., 2008) • L angular gyrus (Kronbichler et al., 2008) Lower white matter in the tracts between: • L auditory cortex & L inferior frontal gyrus (Boets et al., 2013)	Reduced grey matter volume vs controls: • R intraparietal sulcus (Rotzer et al., 2008) Lower white matter in the tracts between: • R fusiform gyrus & R intraparietal sulcus (Rykhlevskaia et al., 2009)
Lesion-Symptom Mapping	Acquired dyslexia associated with damage to: • L inferior frontal gyrus (Kronbichler et al., 2008; Ripamonti et al., 2014b; Shinoura et al., 2010) • R Posterior middle temporal gyrus (Binder et al., 2016) • R fusiform gyrus (Lesniak et al., 2014) • L fusiform gyrus (Leff, 2006; Michel, 2008; Ripamonti et al., 2014b; Turkeltaub et al., 2014) • L angular gyrus, via the posterior cerebral artery (Maeshima et al., 2011; Sharma et al., 2014)	Acquired dyscalculia associated with damage to: • L thalamus (Jensen, 2010; Osawa & Maeshima, 2009) • L angular gyrus (Bhattacharyya, Cai, & Klein, 2014; Ripellino, Terazzi, Mittino, & Cantello, 2013)

3.2.1 Neuroanatomical correlates of reading disability deficits in dyslexia

This systematic review identified a total of fifteen different neuroanatomical regions where atypical function has been reported in research studies on individuals with dyslexia that fit the selection criteria. Among those fifteen structures, three neuroanatomical structures feature prominently in both functional neuroimaging and structural neuroimaging research literature, as well as in case studies of individuals with acquired dyslexia; the *left inferior frontal gyrus*, the *left fusiform gyrus* and the *left angular gyrus.*

Individuals with dyslexia exhibit less activation than controls at the left inferior frontal gyrus (Booth et al., 2007; Brambati et al., 2006; Cao et al., 2006), left fusiform gyrus (Kronbichler et al., 2008; McCrory et al., 2005), and the left angular gyrus (Hoeft et al., 2006; Kronbichler et al., 2006; Meyler et al., 2007; Schulz et al., 2008) when performing the same phonological tasks used to assess in individuals with reading disabilities.

Structural neuroimaging studies have also shown that individuals with dyslexia exhibit reduced grey matter in the left inferior frontal gyrus, fusiform gyrus, and angular gyrus (Kronbichler et al., 2008). Boets et al. (2013) determined that normal readers store phonological representations of words in the left auditory cortex (Brodmann Area 41 and 42), and that a functional connection between the auditory cortex and the left inferior frontal gyrus allows normal readers to access these representations to read more fluently. The same researchers used diffusion tensor imaging to show that the left arcuate fasciculus—the bundle of axons that connect the inferior frontal gyrus to the auditory cortex—has significantly lower white matter in individuals with dyslexia than in controls, while the structure of the auditory cortex itself was left intact. This indicates that individuals with dyslexia develop below average ready fluency in part due to impaired access to phonological representations of words—even words that they are familiar with, exactly as in individuals with reading disabilities.

Finally, lesions to the left fusiform gyrus can cause acquired dyslexia (Leff et al., 2006; Ripamonti et al., 2014b; Roberts et al., 2013; Turkeltaub et al., 2014) or from damage to the left posterior cerebral artery, which supplies blood to the left angular gyrus (Maeshima et al., 2011; Sharma et al., 2014). Lesions to the *pars opercularis* section (Brodmann area 44) of the left inferior frontal gyrus can cause acquired dyslexia, primarily in the form of abrupt deficits in decoding pseudowords (Kronbichler et al., 2008; Ripamonti et al., 2014b), whereas lesions to the *pars triangularis* section (Brodmann area 45) are well-known cause in Broca's aphasia (Berker et al., 1986).

3.2.2 Neuroanatomical correlates of mathematical disability deficits in dyscalculia

The findings of the functional neuroimaging, structural neuroimaging, and lesion-symptom studies in this systematic review suggest that there are two key neurological structures whose dysfunction may produce distinct and pervasive and difficulties with mathematics; the *bilateral intraparietal sulcus* (IPS) and the *left angular gyrus*. Atypical hypoactivation at the right IPS and atypical hyperactivation at the left angular gyrus during mathematical tasks have been associated with specific aspects of impaired mathematical cognition in individuals with dyscalculia.

Individuals with dyscalculia exhibit less activation controls at the bilateral intraparietal sulci (Kaufmann et al., 2009b; Kucian et al., 2006; Mussolin et al., 2009; Price et al., 2007) when performing variants of the non-symbolic magnitude comparison tasks used to assess the quantitative reasoning skills of individuals with mathematical disabilities. They exhibit greater activation than controls at the left angular gyrus when performing these same magnitude comparison tasks (Kaufmann et al., 2009b; Kucian et al., 2006). Structural neuroimaging studies shown that individuals with dyscalculia have lower grey matter volume than controls in the right intraparietal sulcus (Rotzer et al., 2008) as well as lower white matter volume than controls in the, the tract that connects the right intraparietal sulcus to the right fusiform gyrus (Rykhlevskaia et al., 2009).

Furthermore, lesions to either the left thalamic nuclei (Jensen, 2010; Osawa & Maeshima, 2009) or to the left angular gyrus (Bhattacharyya et al., 2014; Ripellino et al., 2013) can produce symptoms of acquired dyscalculia. Direct damage to left angular gyrus from strokes typically results in *Gerstmann's syndrome*, a disorder characterized by a sudden inability to write (agraphia), an inability to recognize ones' own fingers (finger agnosia), left-right disorientation, and a severe impairment performing mathematical tasks (Zukic, Mrkonjic, Sinanovic, Vidovic, & Kojic, 2012).

Discussion

4.1 The Additive Hypothesis of Cognitive Deficits in Comorbid Math and Reading Disabilities

The results of this psychoeducational test battery have provided valuable insight into the cognitive profiles of individuals with comorbid math and reading disabilities. The MDRD participants obtained the lowest mean scores in six out of the seven neuropsychological tests (all except the WRMT-R Word Attack subtest). While this pattern of below-average performance is distinct and consistent with existing literature, this information alone is not enough to ascertain an antagonistic relationship between math disability and reading disability. Following the methods of previous quantitative research studies on dyslexia-dyscalculia comorbidity, a significant interaction between math disability and reading disability in a two-way ANOVA performed on the mean test scores would sufficiently indicate a synergistic or antagonistic relationship (depending on whether the scores demonstrate over-additivity or under-additivity) between the cognitive deficits unique to individuals with math disabilities or individuals with reading disabilities (Landerl et al., 2009; Wilson et al., 2015). In the current research, the bivariate analysis of the mean test scores did not reveal an interaction between reading disability and math disability on the mean scores in any of the seven neuropsychological tests. Therefore, results of this study do not support a synergistic deficit hypothesis or the antagonistic deficit hypothesis for comorbid math and reading disabilities, echoing the findings from studies on the cognitive profiles of comorbid reading-and-math-disabled children (Landerl et al., 2009) and adults (Wilson et al., 2015). Instead, these results lend further support to the additive hypothesis of cognitive deficits; the impaired learning abilities of individuals with comorbid learning disabilities are the sum result of separate, specific, underlying cognitive deficits.

4.2 Domain-Specific Deficits in Comorbid Mathematical and Reading Disabilities

The contrast patterns determined in the univariate analysis only partially correspond with the domain-specific view of learning disabilities. On the three phonological tests, the RD participants and the MDRD participants both had lower performance scores than the participants with no reading disability, exhibiting a considerable and specific deficit in phonological processing. Meanwhile, the MD participants did not exhibit a phonological deficit, scoring well within the typical achievement range. This result follows the well-established predictions from a long history of research on the cognitive deficits observed in dyslexia; it has been shown for several decades that individuals with reading disabilities alone or comorbid reading-and-math disabilities consistently exhibit deficits in phonological processing, frequently making mistakes in applying phoneme-grapheme correspondence rules (Ferrer et al., 2015; Shaywitz, 1998; Snowling, 1981). It is this specific deficit in phonological processing that underlies poor word recognition, and thereby underlies poor reading fluency (Lyon et al., 2003; Norton et al., 2015). In concordance with the domain-specific view of learning disabilities, both individuals with reading disabilities and those with the comorbid condition exhibited distinct impairments in phonological processing, but the impairment in individuals with comorbidity was no more severe than the impairment in individuals with reading disabilities alone.

The results from the KeyMath Interpreting Data subtest do not correspond with the domain-specific view of learning disabilities. According to this viewpoint, individuals with reading disabilities should not exhibit significant deficits on tests of quantitative reasoning, because these types of tests typically assess cognitive processes outside the domain of reading, language, and phonology (Landerl et al., 2004; Shalev, 2004). It was expected that only the math-disabled participants would demonstrate below-average performance on this subtest;

instead, all three of the learning disability groups performed at a lower level than the typical achievement range. Furthermore, the results do not correspond with the domain-additive hypothesis of cognitive deficits; the deficit demonstrated by the MDRD group did not equal the sum of the deficits in the MD and RD groups, contrary to the findings in previous psychometric studies (Grant et al., 2015; Landerl et al., 2009).

The KeyMath Diagnostic Assessment was designed for the screening of overall mathematical achievement in educational settings (Larson & Williams, 1994), not for the purpose of neuropsychological assessment in the general population. The test is limited by low reliability when used to identify specific calculation mechanisms underlying difficulties in the learning disability population (Perez, 1996). In contrast to the tests that have been used to examine mathematical cognition in previous studies on comorbid learning disabilities (Wilson et al., 2015), the Interpreting Data subtest is not an assessment of basic numerical magnitude processing and the approximate number system—which form the core deficit in dyscalculia (Dehaene, 2001); rather, it assesses a variety of linguistic-based applied mathematical skills, including geometry, probability, and pattern recognition. Namely, successful completion of this subtest relies heavily on intact reading comprehension and writing abilities; the standardized scores obtained from this test correlate only modestly with impairments to verbal, phonological, or linguistic processing, but do correlate well with more general skills such as verbal and linguistic reasoning such as Kaufman Test of Educational Achievement, Iowa Tests of Basic Skills, Measures of Academic Progress, and Group Math Assessment and Diagnostic Evaluation (Rosli, 2011). In this subtest, each participant is presented with a written passage containing a quantitative reasoning problem, for which they must devise a plan to determine an exhaustive list of possible answers. They are not tasked with manipulating or comparing unfamiliar nonsymbolic quantities—a hallmark of quantitative skills testing for dyscalculia (Bugden & Ansari, 2015b; Butterworth, 2011). In summary, while the KeyMath Interpreting Data subtest is a valid measure of applied mathematical skills mediated by linguistic comprehension, it is not finely-tuned enough to detect the specific cognitive deficits that are unique to individuals with dyscalculia, but identifies shared linguistic and comprehension deficits in comorbid mathematical and reading disabilities. Therefore, the contrast patterns determined in the univariate analysis determined that all three learning disability groups demonstrated deficits in successfully applying mathematical principles to solve written word problems, but these patterns cannot be interpreted as valid indicators of a computational or quantitative deficit in numerical magnitude processing.

4.3 Domain-General Deficits in Comorbid Reading and Mathematical Disability

The contrast patterns determined in the univariate analysis of the WAIS-R/WISC-III, Block Design, Vocabulary, Digit Span subtests correspond to a greater extent with the domain-general view of specific learning disabilities. On the Block Design subtest, the MD and MDRD groups both performed far below the typical achievement level, suggesting that individuals with mathematical disabilities experience a pervasive deficit in visuospatial reasoning. This result may be explained by the cognitive mechanisms that play in role in spatial perception tasks and performing mathematical operations. When performing a test of visuospatial reasoning such as the Block Design task, the participants make perceptual approximations about a group shapes and how they can be rearranged to match a two-dimensional geometric pattern. This ability to make visual approximations may be negatively influenced by impaired access to the approximate number system—the cognitive mechanism that allows to make estimations about objects and other nonsymbolic quantities, and manipulate them in mathematical operations (Dehaene, 2001).

This cognitive system is persistently impaired in individuals with mathematical disabilities (Bugden & Ansari, 2015b; Butterworth, 2011) and is correlated with impaired perceptual reasoning skills (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013). Studies that used functional neuroimaging to examine performance on a mental calculation task and the Corsi Blocks task (a test of visuospatial pattern recognition) reported a strong correlation between deficits in visuospatial ability and the presence of a math disability. (Kyttälä & Lehto, 2008; Zago et al., 2001).

In contrast to the math-disabled participants, the RD group did not demonstrate a deficit in visuospatial reasoning; remarkably, they scored higher on average than participants in typical achievement range. Individuals with reading disabilities have previously shown to match the performance of non-learning-disability participants on various iterations of this visuospatial reasoning task (Landerl et al., 2009; von Károlyi et al., 2003). It has been proposed that reading-disabled individuals may compensate for deficits in phonological processing by relying on higher cognitive skills such as visuospatial reasoning to learn, recognize, and articulate words (Bacon & Handley, 2014; Schneps et al., 2007). However, while RD individuals have consistently shown faster response times (but not greater accuracy) in their ability to quickly identify impossible figures and manipulate complex shapes with blocks, there is little evidence to suggest they possess an advantage in spatial processing (Gilger, Allen, & Castillo, 2016).

The most noteworthy findings of the current study were obtained from the WAIS-R Vocabulary and Digit Span subtests. On the Vocabulary subtest, the MD group and the RD group performed at a statistically-equivalent level; both groups scored significantly lower on average than the typical achievement range, implying that both groups experienced a specific difficulty in articulating age-appropriate word definitions. This was an unexpected finding for the MD group in particular; individuals with math disabilities are not known to demonstrate difficulty in word recognition, especially when tested on with familiar words instead of pseudowords. The difficulty demonstrated by the RD group was also unexpected, because the Vocabulary subtest does not directly assess phonological processing. The participants did not need to read any of the items (they were read by a test administrator), nor were any of the words considered to be too irregular for their age-appropriate lexicon (common words such as "clock", or "alphabet" were prompted on the WISC). Given that the between-group differences in education rating were insignificant and none of the participants had an estimated IQ within the clinically-critical range, it was not expected that this task would evoke any significant differences between the learning disability groups.

It was originally hypothesized that individuals with comorbid math and reading disabilities would not exhibit additive deficits on the Vocabulary subtest because it does not exclusively assess domain-specific phonological processing or arithmetic abilities. The MDRD participants performed at an even lower level than the both the MD group and the RD group. While the mean difference between the RD and MDRD narrowly missed statistical significance ($p = 0.069$), the difference in mean scaled scores between the TA and MDRD groups (4.34) was nearly the sum of the difference between the TA and MD groups (1.95) and the difference between the TA and RD groups (3.10), corresponding with the additive hypothesis of deficits in MDRD. In stark contrast, the individual deficits shown by the MD and RD groups and the additive deficits exhibited by the MDRD group suggest that an impairment to some other domain-general cognitive system mediates their ability to articulate definitions of common words.

The groups' performances on the Digit Span subtest followed a nearly identical pattern to the trend seen on the Vocabulary subtest. The MD and RD groups performed at a statistically-even level—both groups significantly lower than the typical achievement range—indicating that these participants experienced a specific deficit in verbal working memory. Just as in the Vocabulary subtest, the MDRD group performed at even lower level on average than the single-disability groups. In support of the additive hypothesis, the mean difference in scores between the TA and MDRD groups (3.57) was slightly more than the sum of the difference between the TA and MD groups (1.68) and the difference between the TA and RD groups (1.57); as described in section 4.1, this over-additivity was not the result of a significant interaction between math disability and reading disability, and therefore does not fit the synergistic hypothesis. These results suggest that individuals with math disabilities or reading disabilities alone present a specific, persistent impairment to their verbal working memory system, and that this impairment is even more pronounced in individuals with comorbid math and reading disabilities in a manner that is both scientifically and clinically significant.

The verbal working memory deficit reported in the RD and MDRD groups was consistent with evidence from previous studies; individuals with reading disabilities consistently demonstrate impaired working memory (Swanson et al., 2006; Vasic et al., 2008a; A. M. Wilson & Lesaux, 2001). The deficit demonstrated by the MD group, however, was not expected. Previous investigations about the relationship between math disability and impaired working memory have yielded mixed results. In some studies, individuals with math disabilities exhibit deficits in working memory only when performing tasks that assess working memory and visuospatial reasoning simultaneously (Bugden & Ansari, 2015b; Kyttälä & Lehto, 2008); the Block Design subtest used in this archival study does not test these constructs simultaneously, because the prompt remains visible to the participant at all times (thereby remaining accessible in the participant's short-term sensory memory).

In other studies, individuals with math disabilities do not exhibit any significant deficits relative to controls when performing forward or backward recall tasks (Mammarella, Hill, Devine, Caviola, & Szucs, 2015); but when wider selection criteria is used to classify participants into control and math disability groups (e.g. those who perform below the 30th percentile on a standardized arithmetic test), the math disability group's participants perform poorer on average than controls on memory span (Geary, Hoard, & Hamson, 1999; Passolunghi & Siegel, 2004). Given this contradicting evidence, it was hypothesized that the MD participants in the current study would not demonstrate a specific impairment to their working memory system; instead, the MD group did demonstrated pervasive difficulties in performing the working memory task.

Furthermore, the MDRD group—who were expected to exhibit a working memory deficit as seen in individuals with dyslexia—performed significantly poorer than both the MD and RD groups. Reminiscent of the trend seen on the WAIS-R Vocabulary subtest, the difference in mean scaled scores between the TA and MDRD groups (2.21) was approximately even to the combined sum of the difference between the TA and MD groups (1.88) and the difference between the TA and RD groups (0.83). This provides further support to the additive hypothesis; impairments to both the deficit in verbal working memory. An additive working memory deficit in MDRD participants has been demonstrated once before; Wilson et al. (2015) reported that comorbid adults performed significantly poorer than both individuals with MD and those with RD on verbal or numerical working memory tasks.

On the contrary, Landerl et al. (2009) reported that children with a math disability or reading disability alone did not exhibit significant deficits in working memory, but those with comorbid math and reading disabilities did—only on the backward-recall trials (and not the forward-recall trials) of the WISC-III Digit Span subtest. Their statistical analysis revealed a significant interaction between math disability and reading disability on the comorbid group's mean scores on the backward Digit Span subtest, a result that they suggested could offer moderate support to the synergistic deficit hypothesis, but one that was not replicated in the current study. While it is unlikely that a deficit in working memory is the mechanism that underlies all forms of impaired numerical magnitude processing (Wilson & Dehaene, 2007), the current results show that is the case in linguistically-mediated math disability since two separate, independent impairments to numerical cognition and reading ability contribute to a persistent, more severe working memory deficit unique to individuals with comorbid math and reading disabilities.

4.4 A Neuroeducational model of Comorbid Mathematical and Reading Disabilities

The primary objectives of the current study were to (A) measure the cognitive deficits exhibited by individuals with math and reading disabilities, and (B) to map these deficits to their neuroanatomical correlates, in order to provide a neuroeducational model of comorbidity for testing in future research. The performance of the MDRD participants on the psychoeducational tasks in this study revealed two specific cognitive functions that are more severely impaired in comorbidity than in single-disability. As expected, the MDRD group presented domain-specific deficits equal to those shown by the single-disability groups; their scores were on par with the RD group on two of the three phonological tasks, and also matched the performance of the MD group on the test of quantitative reasoning. More importantly, the MDRD participants exhibited domain-general deficits in verbal sematic retrieval and verbal working memory. In both the semantic memory task and the working memory task, the magnitude of the MDRD group's deficit was approximately the sum of the separate deficits demonstrated by the MD and RD groups. These findings lend strong support to the additive deficit hypothesis. From a cognitive perspective, independent math disability and an independent reading disability combined to produce a greater deficit in semantic memory and a larger deficit in working memory—deficits that were greater in magnitude than those observed in the participants with a single disability.

The model hereby presented proposes that left angular gyrus is the key neurological structure that mediates the cognitive deficits uniquely expressed in both math and reading disabilities; previous studies have shown that atypical function of the left and angular gyrus is associated with deficits in phonological processing, numerical cognition, and working memory—all of which were exhibited by the MDRD participants in the current study.

Five strands of evidence form the basis for this hypothesis. First, functional neuroimaging studies have consistently identified the left angular gyrus as a pivotal structure in mediating word recognition, word decoding, and reading comprehension in normal readers (Horwitz, Rumsey, & Donohue, 1998; Meyler et al., 2007; Pugh, Mencl, et al., 2000). individuals with reading exhibit less activation than normal readers at the left angular gyrus during tasks that involve effortful word decoding (such as the Word Attack subtest in this study), and also show decreased activation during semantic processing of visual and auditory words (Demonet et al. 1992; Vandenberghe et al., 1996; Binder and others 2009). In comparison to controls, individuals with dyslexia show atypical hypoactivity at the left angular gyrus while performing phonological tasks (Maisog et al., 2008; Richlan et al., 2009) as well in individuals with dyscalculia while performing tasks that test the approximate number system (Dehaene et al., 2003; Price, 2008). Second, lesions to the posterior cerebral artery (the blood supply of the left angular gyrus) produces symptoms of acquired dyslexia (Sharma et al., 2014), while lesions to the gyrus itself can produce acquired dyscalculia, alongside other symptoms of Gerstmann's syndrome (Nagaratnam, Phan, Barnett, & Ibrahim, 2002).

Third, the left angular gyrus has been shown to mediate the two aspects of memory retrieval: the retrieval of phonetic representations of familiar words (Boets et al., 2013) and the retrieval of arithmetic facts (Grabner et al., 2009). The latter demonstrates a contrast in the type of calculations the right hemisphere and left hemisphere; the right intraparietal sulcus is associated with greater activation for processing inexact quantities for calculations that test the approximate number system, while the left angular gyrus and left intraparietal sulcus are involved in retrieving exact quantities for calculations that require a single correct solution. In addition, the left angular gyrus has shown low functional connectivity with the inferior frontal and left fusiform gyri during phonological processing tasks (Horwitz et al., 1998; Pugh, Einar Mencl, et al., 2000).

Fourth, impairments to subcomponents of working memory can be mapped to the disruption frontal-lobe-to-parietal-lobe association fibers, converging the left angular gyrus. According to Baddeley's Model of Working Memory (Baddeley & Hitch, 1974), a subcomponent of working memory called the phonological loop facilitates the short-term storage encoding verbal information into long-term memory. In Positron Emission Tomography (PET) studies with normal readers performing pseudowords tasks similar to the psychoeducational tests used to examine individuals with reading disabilities, researchers have shown that the angular gyrus is directly active in facilitating the short-term storage and retrieval of unfamiliar phonemic sequences (Jonides et al., 1998; Vasic, Lohr, Steinbrink, Martin, & Wolf, 2008b).

Lastly, applying transcranial magnetic stimulation (TMS) to the left angular gyrus has been shown to increase the accuracy of semantic memory when pairing stimuli for classical conditioning (Davey et al., 2015), but can also cause deficits in visuospatial reasoning, mainly right-left disorientation. This collection of evidence from functional imaging, lesion-symptom analysis, and neuropsychology research provide valuable insight into the unique role of the left angular gyrus in mediating the cognitive deficits shared in math and reading disabilities.

The MDRD participants demonstrated additive domain-general deficits in verbal working memory and verbal semantic memory, which suggests a functional relationship between the verbal, expressive component of these deficits, and the retrieval of symbolic and semantic representations of words from long-term memory. A possible explanation is that a pervasive deficit to the verbal working memory system (specifically the phonological loop subcomponent in Baddeley's model) impairs both the short-term storage of basic verbal information and the retrieval of semantic information from long-term storage. The model shown in Figure 10 proposes that a pervasive deficit in the temporary storage of verbal information is an additional core deficit unique to individuals with comorbid dyslexia-dyscalculia, associated with atypical function of the left angular gyrus.

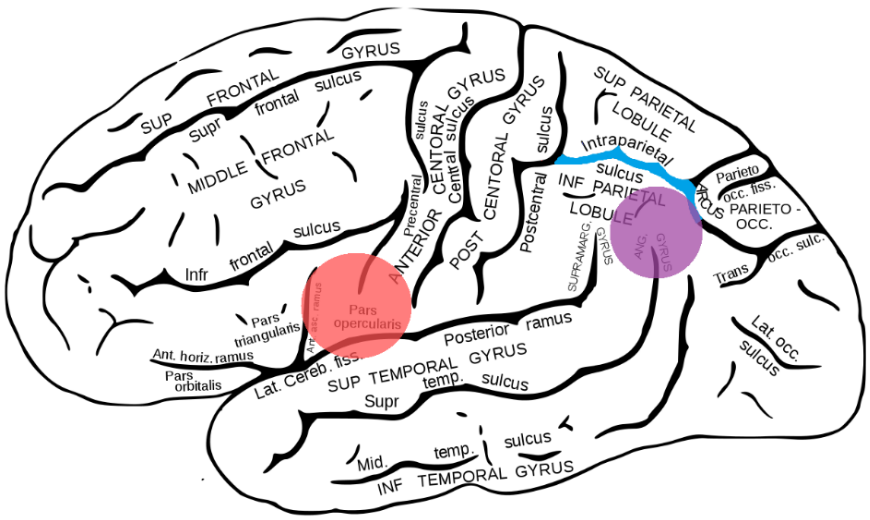


Figure 10. A neuroeducational model of dyslexia-dyscalculia comorbidity. Image obtained from Gray, 2000. The *left pars opercularis* region is highlighted in red, the *left intraparietal sulcus* is highlighted in blue, and the *left angular gyrus* is highlighted in purple.

In summary, converging evidence from neuroimaging and psychoeducational research suggests that impaired phonological, numerical, semantic, and working memory processes are associated with atypical function of the left angular gyrus in both math and disabilities. Individuals with dyslexia exhibit atypical hypoactivation at the inferior frontal gyrus when performing the same psychoeducational tests that are used to assess phonological processing deficits in individuals with reading disabilities. Individuals with dyslexia also exhibit atypical hypoactivation at the visual word form area of the left fusiform gyrus (located on the sagittal surface of the temporal lobe) when viewing written words, and consistently demonstrate impaired word recognition, similar to the deficits seen in individuals with reading disabilities when performing psychoeducational tests of vocabulary and reading fluency.

Individuals with dyscalculia exhibit atypical hypoactivation of the bilateral intraparietal sulci when performing numerical magnitude processing tasks, akin to the psychoeducational tests used to assess the function of the approximate number system in individuals with mathematical disabilities. The left angular gyrus is the only neuroanatomical region that corresponds with overlapping impairments in individuals with dyslexia and those with dyscalculia.

Individuals with dyslexia exhibit atypical hypoactivation at this region when performing word definition recall tasks, demonstrating the same deficits in semantic memory that are seen in individuals with reading disabilities when performing the WAIS-R Vocabulary task. Individuals with dyscalculia exhibit atypical hyperactivation at the left angular gyrus when retrieving arithmetic facts, presenting similar difficulties as individuals with math disabilities when performing psychoeducational tests that assess basic math fluency.

Conclusions

In agreement with the findings of previous studies, individuals with comorbid math and reading disabilities demonstrate domain-specific deficits equivalent to single-disability individuals. In contribution to the existing research, comorbid individuals also demonstrate additive domain-general deficits in verbal working memory and verbal semantic memory. The domain-specific reading deficits can be mapped to developmental differences at the left inferior frontal and fusiform gyri, and mathematical deficits can be traced to developmental differences at the bilateral intraparietal sulci. The current model proposes that domain-general, additive deficits in semantic memory and verbal working memory—two pervasive impairments that are unique to neuropsychological profile of individuals with comorbid math and read—are the result of developmental differences at the left angular gyrus.

Appendices

A.1 Wide Range Achievement Test (WRAT3) – Arithmetic Subscale

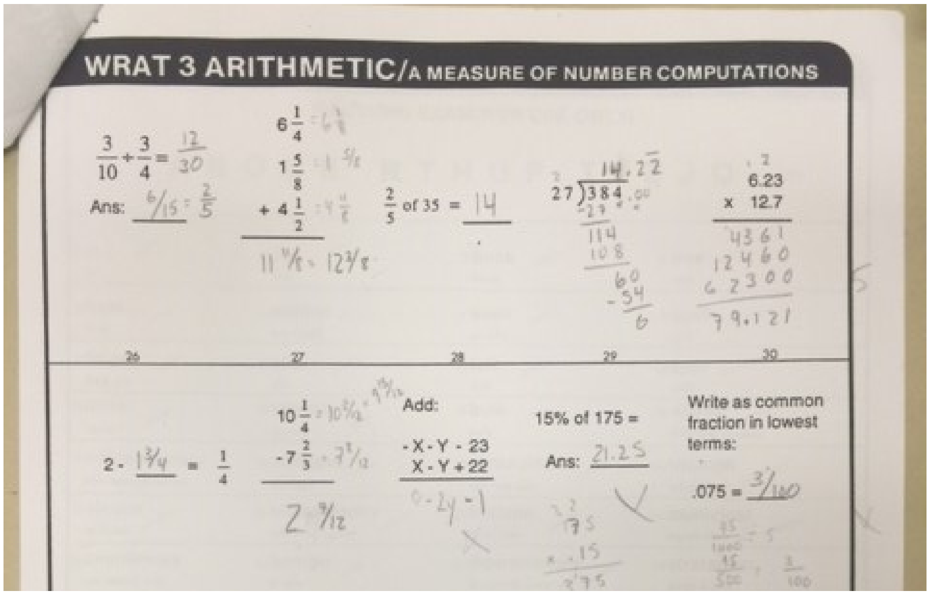


Table 6

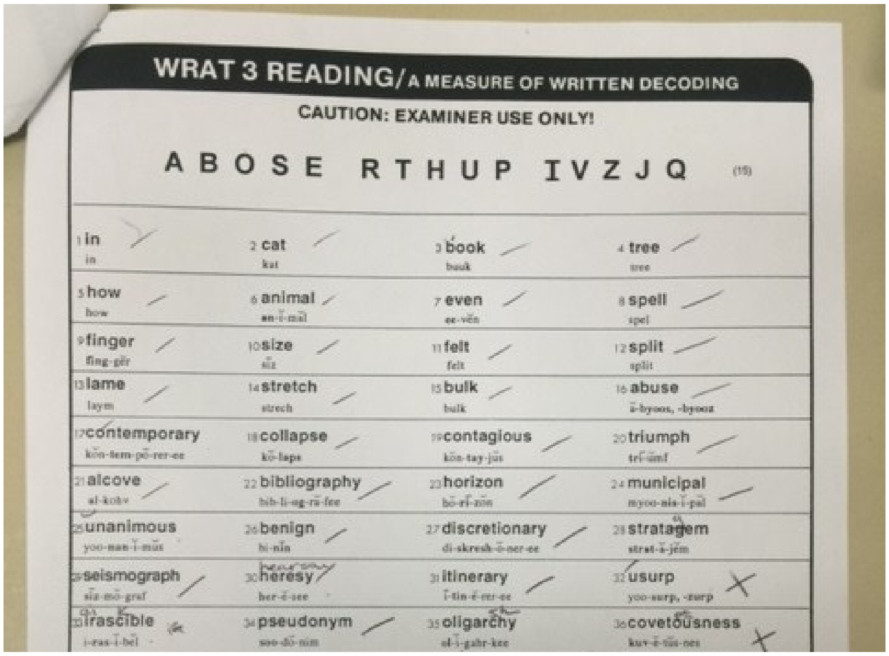
Tukey Post-Hoc Multiple Comparisons for the WRAT3 Arithmetic Subscale

Multiple Comparisons

Dependent Variable: WRAT3: Arithmetic (Blue) Percentile Rank

(I) Learning Disability Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
TA	MD	44.5619*	2.17330	.000	38.9522	50.1716
	RD	7.5619*	2.52329	.015	1.0488	14.0750
	MDRD	47.4780*	2.01073	.000	42.2878	52.6681
MD	TA	-44.5619*	2.17330	.000	-50.1716	-38.9522
	RD	-37.0000*	2.86685	.000	-44.3999	-29.6001
	MDRD	2.9160	2.42794	.627	-3.3510	9.1830
RD	TA	-7.5619*	2.52329	.015	-14.0750	-1.0488
	MD	37.0000*	2.86685	.000	29.6001	44.3999
	MDRD	39.9160*	2.74566	.000	32.8289	47.0032
MDRD	TA	-47.4780*	2.01073	.000	-52.6681	-42.2878
	MD	-2.9160	2.42794	.627	-9.1830	3.3510
	RD	-39.9160*	2.74566	.000	-47.0032	-32.8289

A.2 Wide Range Achievement Test (WRAT3) – Reading Subscale



WRAT 3 READING/A MEASURE OF WRITTEN DECODING

CAUTION: EXAMINER USE ONLY!

A B O S E R T H U P I V Z J Q (15)

1 in	2 cat	3 book	4 tree
5 how	6 animal	7 even	8 spell
9 finger	10 size	11 felt	12 split
13 lame	14 stretch	15 bulk	16 abuse
17 contemporary	18 collapse	19 contagious	20 triumph
21 alcove	22 bibliography	23 horizon	24 municipal
25 unanimous	26 benign	27 discretionary	28 stratagem
29 seismograph	30 heresy	31 itinerary	32 usurp
33 irascible	34 pseudonym	35 oligarchy	36 covetousness

Table 7

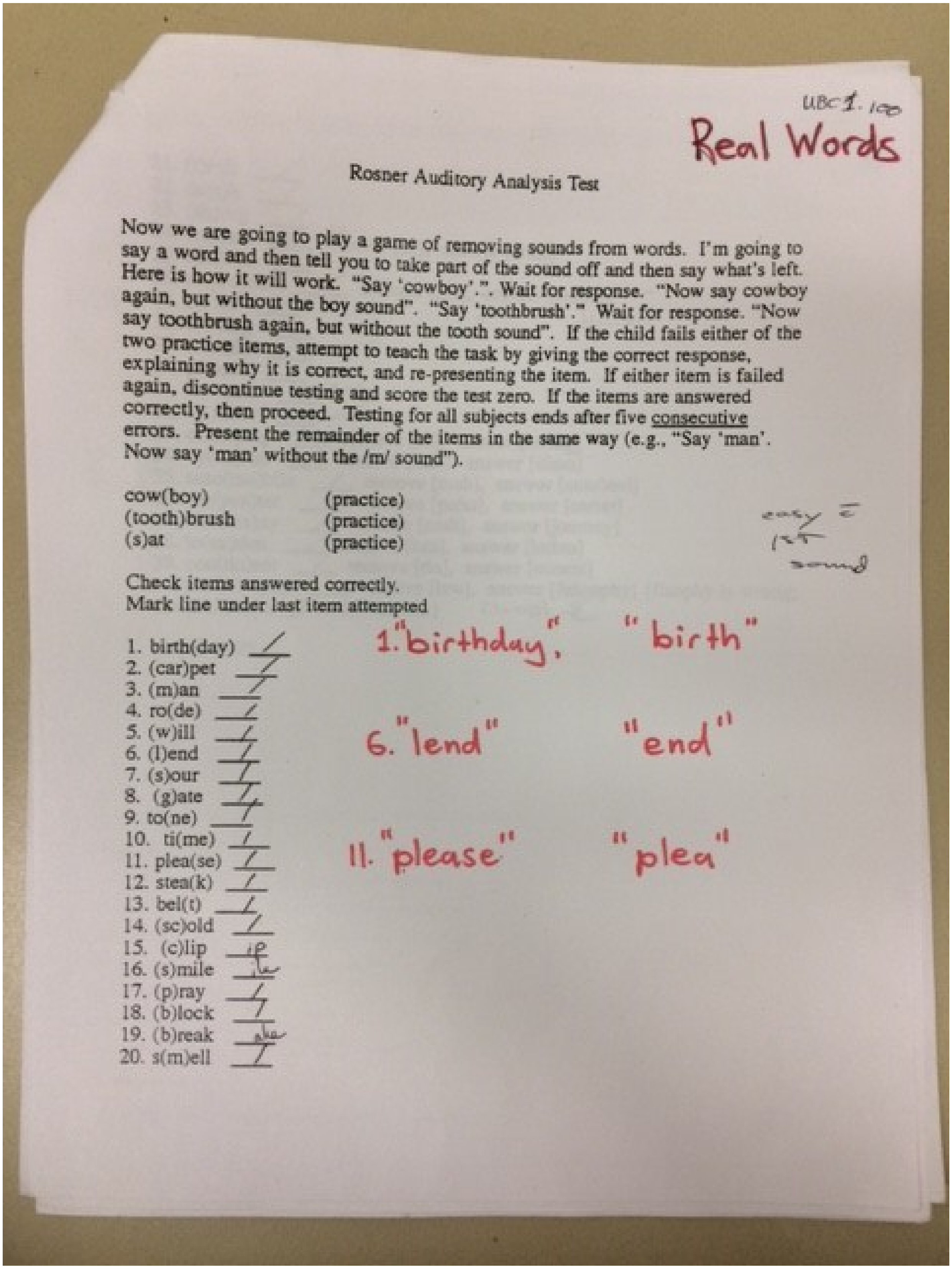
Tukey Post-Hoc Multiple Comparisons for the WRAT3 Reading Subscale

Multiple Comparisons

Dependent Variable: WRAT3: Reading Percentile Rank
Tukey HSD

(I) Learning Disability Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
TA	MD	10.4241*	2.25409	.000	4.6058	16.2423
	RD	51.3371*	2.61709	.000	44.5818	58.0923
	MDRD	53.2861*	2.08548	.000	47.9031	58.6692
MD	TA	-10.4241*	2.25409	.000	-16.2423	-4.6058
	RD	40.9130*	2.97342	.000	33.2380	48.5881
	MDRD	42.8621*	2.51820	.000	36.3621	49.3621
RD	TA	-51.3371*	2.61709	.000	-58.0923	-44.5818
	MD	-40.9130*	2.97342	.000	-48.5881	-33.2380
	MDRD	1.9490	2.84773	.903	-5.4016	9.2996
MDRD	TA	-53.2861*	2.08548	.000	-58.6692	-47.9031
	MD	-42.8621*	2.51820	.000	-49.3621	-36.3621
	RD	-1.9490	2.84773	.903	-9.2996	5.4016

A.3 Rosner Auditory Analysis task



UBC1.100

Real Words

Rosner Auditory Analysis Test

Now we are going to play a game of removing sounds from words. I'm going to say a word and then tell you to take part of the sound off and then say what's left. Here is how it will work. "Say 'cowboy'.". Wait for response. "Now say cowboy again, but without the boy sound". "Say 'toothbrush'." Wait for response. "Now say toothbrush again, but without the tooth sound". If the child fails either of the two practice items, attempt to teach the task by giving the correct response, explaining why it is correct, and re-presenting the item. If either item is failed again, discontinue testing and score the test zero. If the items are answered correctly, then proceed. Testing for all subjects ends after five <u>consecutive</u> errors. Present the remainder of the items in the same way (e.g., "Say 'man'. Now say 'man' without the /m/ sound").

cow(boy) (practice)
(tooth)brush (practice)
(s)at (practice)

easy = 1st sound

Check items answered correctly.
Mark line under last item attempted

1. birth(day)
2. (car)pet
3. (m)an
4. ro(de)
5. (w)ill
6. (l)end
7. (s)our
8. (g)ate
9. to(ne)
10. ti(me)
11. plea(se)
12. stea(k)
13. bel(t)
14. (sc)old
15. (c)lip
16. (s)mile
17. (p)ray
18. (b)lock
19. (b)reak
20. s(m)ell

1. "birthday". "birth"

6. "lend" "end"

11. "please" "plea"

Table 8

Descriptive Statistics for the Rosner Auditory Analysis task.

Descriptives

Reading Test 1 - Phoneme Deletion: Rosner Raw Score

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
TA	158	31.77	8.56	.68099	30.4271	33.1172	3.00	40.00
MD	69	29.94	8.93	1.07535	27.7962	32.0879	0.00	39.00
RD	46	23.48	9.53	1.40487	20.6487	26.3078	4.00	38.00
MDRD	87	21.30	10.31	1.10552	19.1012	23.4965	0.00	37.00
Total	360	27.8306	10.22105	.53870	26.7712	28.8900	0.00	40.00

Table 9

Tukey Post-Hoc Multiple Comparisons for the Rosner Auditory Analysis task

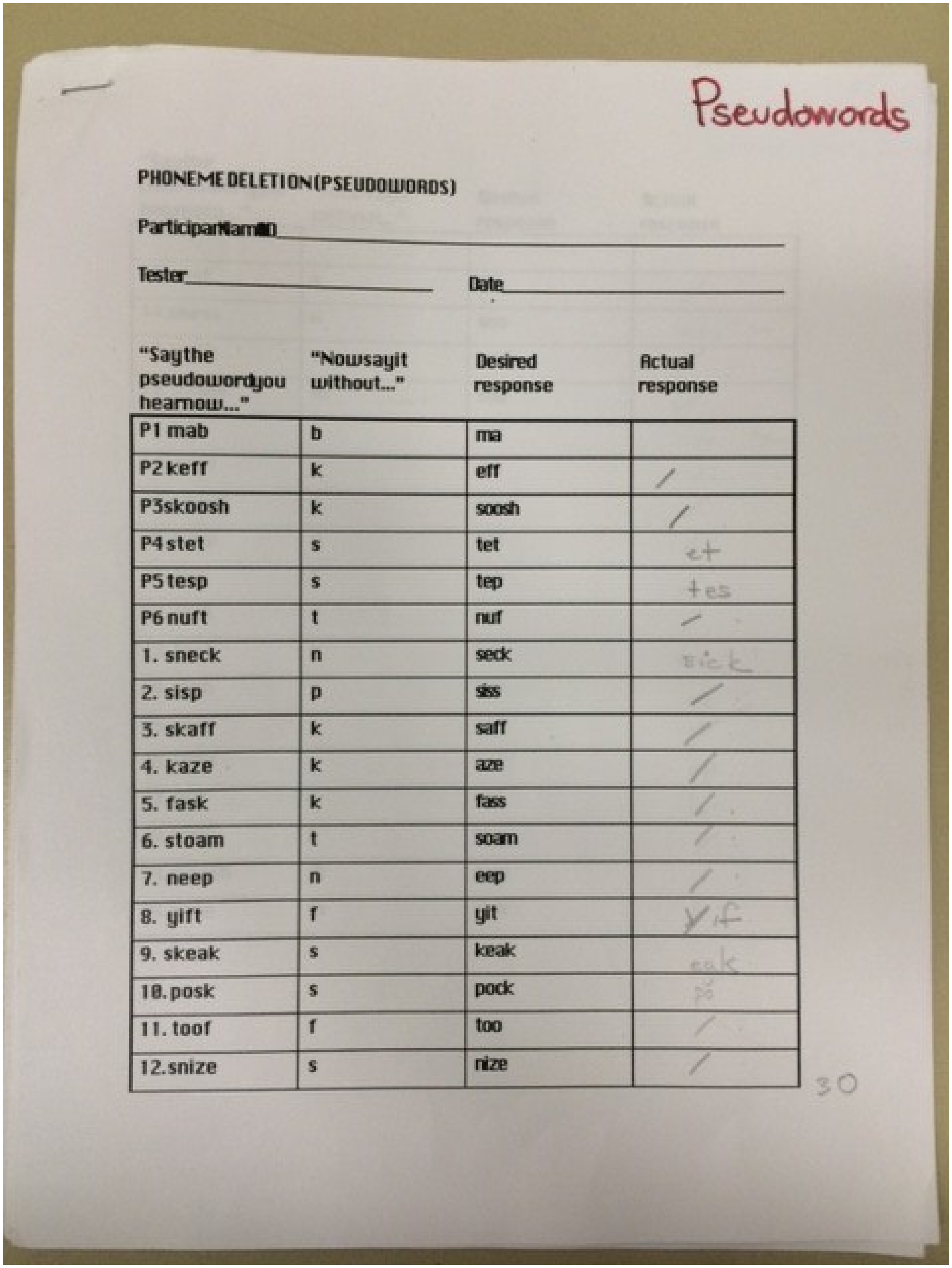
Multiple Comparisons

Dependent Variable: Reading Test 1 - Phoneme Deletion: Rosner Score
Tukey HSD

(I) Disability Group	(J)	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
TA	MD	1.83012	1.32814	.514	-1.5981	5.2583
	RD	8.29389*	1.54203	.000	4.3136	12.2742
	MDRD	10.47330*	1.22880	.000	7.3015	13.6451
MD	TA	-1.83012	1.32814	.514	-5.2583	1.5981
	RD	6.46377*	1.75199	.001	1.9415	10.9860
	MDRD	8.64318*	1.48376	.000	4.8133	12.4731
RD	TA	-8.29389*	1.54203	.000	-12.2742	-4.3136
	MD	-6.46377*	1.75199	.001	-10.9860	-1.9415
	MDRD	2.17941	1.67793	.564	-2.1517	6.5105
MDRD	TA	-10.4733*	1.22880	.000	-13.6451	-7.3015
	MD	-8.64318*	1.48376	.000	-12.4731	-4.8133
	RD	-2.17941	1.67793	.564	-6.5105	2.1517

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

A.4 Pseudowords Phoneme Deletion task



Pseudowords

PHONEME DELETION (PSEUDOWORDS)

Participant Name/ID ____________________

Tester ____________________ Date ____________________

"Say the pseudoword you hear now..."	"Now say it without..."	Desired response	Actual response
P1 mab	b	ma	
P2 keff	k	eff	/
P3 skoosh	k	soosh	/
P4 stet	s	tet	et
P5 tesp	s	tep	tes
P6 nuft	t	nuf	/
1. sneck	n	seck	sick
2. sisp	p	siss	/
3. skaff	k	saff	/
4. kaze	k	aze	/
5. fask	k	fass	/
6. stoam	t	soam	/
7. neep	n	eep	/
8. yift	f	yit	yif
9. skeak	s	keak	eak
10. posk	s	pock	po
11. toof	f	too	/
12. snize	s	nize	/

30

Table 10

Descriptive Statistics for the Pseudowords Phoneme Deletion task.

Descriptives

Reading Test 2 - Phoneme Deletion: Pseudowords Raw Score

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
TA	158	22.09	7.39	.58767	20.9279	23.2494	0.00	30.00
MD	69	21.17	6.93	.83430	19.5091	22.8387	0.00	30.00
RD	46	15.93	7.06	1.04044	13.8392	18.0303	0.00	30.00
MDRD	87	12.25	7.37	.78991	10.6826	13.8232	0.00	26.00
Total	360	18.7500	8.33583	.43934	17.8860	19.6140	0.00	30.00

Table 11

Tukey Post-Hoc Multiple Comparisons for the Pseudowords Phoneme Deletion task

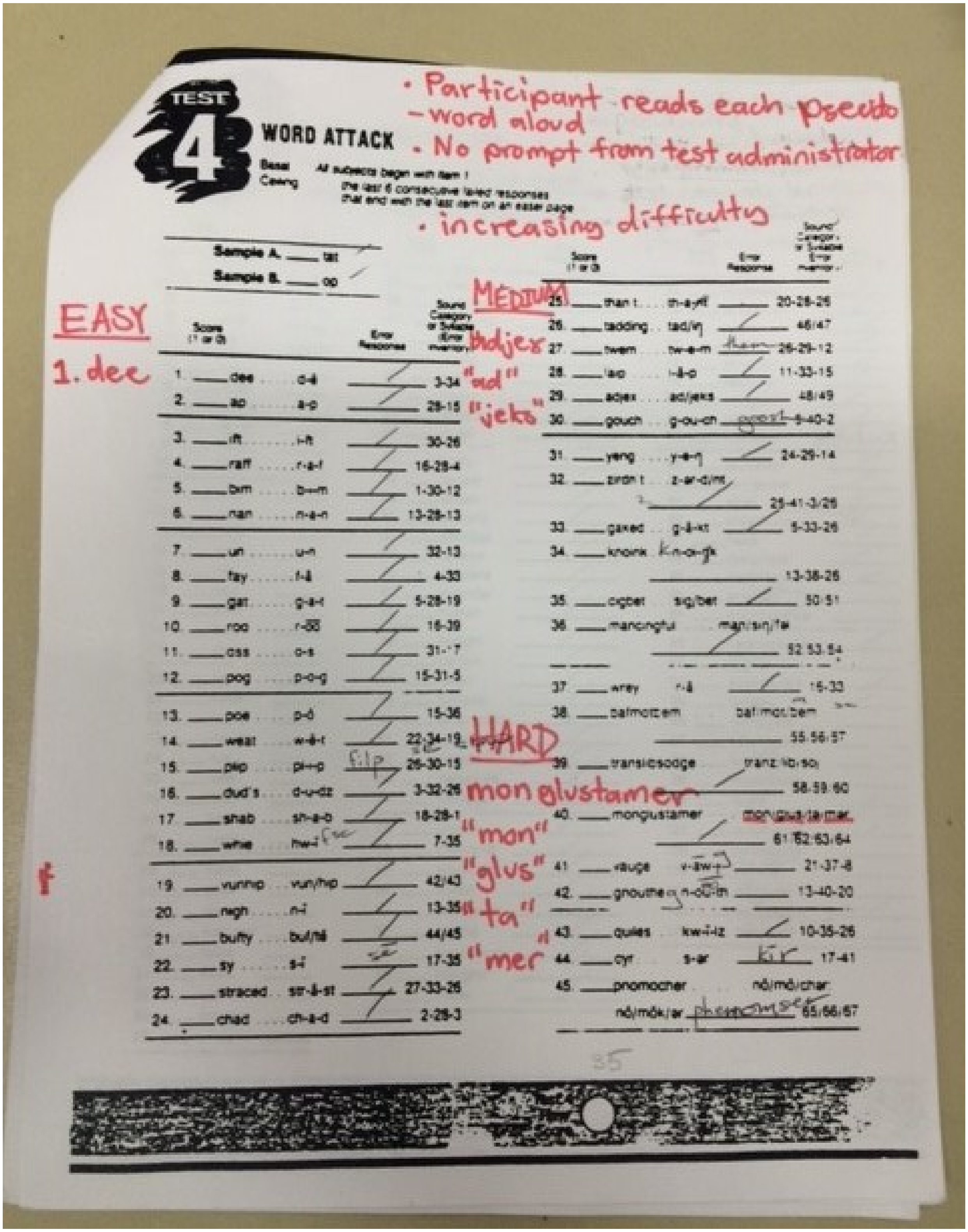
Multiple Comparisons

Dependent Variable: Reading Test 2 - Phoneme Deletion: Pseudowords Score
Tukey HSD

(I) Disability Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
TA	MD	0.91	1.04699	.819	-1.79	3.62
	RD	6.15	1.21560	.000	3.02	9.29
	MDRD	9.84	.96867	.000	7.34	12.34
MD	TA	-0.91	1.04699	.819	-3.62	1.79
	RD	5.24	1.38111	.001	1.67	8.80
	MDRD	8.92	1.16966	.000	5.90	11.94
RD	TA	-6.15382*	1.21560	.000	-9.29	-3.02
	MD	-5.23913*	1.38111	.001	-8.80	-1.67
	MDRD	3.68	1.32272	.029	0.27	7.10
MDRD	TA	-9.83573*	.96867	.000	-12.34	-7.34
	MD	-8.92104*	1.16966	.000	-11.94	-5.90
	RD	-3.68191*	1.32272	.029	-7.10	-0.27

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

A.5 WMRT-R Word Attack subtest



TEST 4 WORD ATTACK

Basal: All subjects begin with item 1

Ceiling: the last 6 consecutive failed responses that end with the last item on an easel page

• Participant reads each pseudo-word aloud

• No prompt from test administrator

• increasing difficulty

Sample A. ___ tat

Sample B. ___ op

EASY

1. dee

Score (1 or 0)			Error Responses	Sound Category or Syllable (Error Inventory)
1.	dee	d-ē		3-34
2.	ap	ă-p		29-15
3.	ift	i-ft		30-26
4.	raff	r-ă-f		16-28-4
5.	bim	b-i-m		1-30-12
6.	nan	n-ă-n		13-28-13
7.	un	u-n		32-13
8.	fay	f-ā		4-33
9.	gat	g-ă-t		5-28-19
10.	roo	r-ōō		16-39
11.	oss	o-s		31-17
12.	pog	p-o-g		15-31-5
13.	poe	p-ō		15-36
14.	weat	w-ē-t		22-34-19
15.	pip	pi-p	flip	26-30-15
16.	dud's	d-u-dz		3-32-26
17.	shab	sh-ă-b		18-28-1
18.	whie	hw-ī		7-35
19.	vunhip	vun/hip		42/43
20.	nigh	n-ī		13-35
21.	bufty	buf/tē		44/45
22.	sy	s-ī		17-35
23.	straced	str-ā-st		27-33-26
24.	chad	ch-ă-d		2-28-3

MEDIUM

"adjer"

"ad"

"jeks"

Score (1 or 0)			Error Responses	Sound Category or Syllable (Error Inventory)
25.	thent	th-ĕ-nt		20-28-26
26.	tadding	tad/ing		46/47
27.	twem	tw-e-m	them	26-29-12
28.	laip	l-ā-p		11-33-15
29.	adjex	ad/jeks		48/49
30.	gouch	g-ou-ch	gourt	5-40-2
31.	yeng	y-e-ŋ		24-29-14
32.	zirdn't	z-ar-d/nt		25-41-3/26
33.	gaked	g-ā-kt		5-33-26
34.	knoink		Kn-oink	13-38-26
35.	cigbet	sig/bet		50/51
36.	mancingful	man/sin/fəl		52/53/54
37.	wrey	r-ā		16-33
38.	bafmotbem	baf/mot/bem		55/56/57
39.	translibsodge	tranz/lib/soj		58/59/60
40.	monglustamer	mon/glus/tə/mər		61/62/63/64
41.	vauge	v-âw-j		21-37-8
42.	gnouthe	n-ou-th		13-40-20
43.	quies	kw-ī-iz		10-35-26
44.	cyr	s-ər	Kir	17-41
45.	pnomocher	nō/mō/chər, nō/mōk/ər	phenomoser	65/66/67

HARD

monglustamer

"mon"

"glus"

"ta"

"mer"

35

Table 12

Descriptive Statistics for the Word Attack subtest

Descriptives

Reading Test 3 - Word Attack Raw Score

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
TA	158	32.80	9.30	.73972	31.3364	34.2586	1.00	44.00
MD	69	33.25	8.17	.98311	31.2846	35.2081	0.00	44.00
RD	46	20.15	10.24	1.50938	17.1121	23.1922	3.00	43.00
MDRD	87	20.24	10.50	1.12527	18.0044	22.4783	0.00	41.00
Total	360	28.2333	11.30538	.59585	27.0615	29.4051	0.00	44.00

Table 13

Tukey Post-Hoc Multiple Comparisons for the Word Attack subtest

Multiple Comparisons

Dependent Variable: Reading Test 3 - Word Attack Raw Score
Tukey HSD

(I) Disability Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
TA	MD	-0.45	1.37	0.988	-4.00	3.10
	RD	12.65	1.60	0.000	8.53	16.76
	MDRD	12.56	1.27	0.000	9.27	15.84
MD	TA	0.45	1.37	0.988	-3.10	4.00
	RD	13.09	1.81	0.000	8.41	17.77
	MDRD	13.01	1.54	0.000	9.04	16.97
RD	TA	-12.65	1.60	0.000	-16.76	-8.53
	MD	-13.09	1.81	0.000	-17.77	-8.41
	MDRD	-0.09	1.74	1.000	-4.57	4.39
MDRD	TA	-12.55609*	1.27162	.000	-15.8384	-9.2738
	MD	-13.00500*	1.53547	.000	-16.9684	-9.0416
	RD	.08921	1.73641	1.000	-4.3928	4.5712

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

A.6 KeyMath Interpreting Data Subtest

Correct Response

10. **Here are some chips numbered zero to nine.** **Using two chips at a time, tell me all the ways to make a total of eleven.**	9 and 2, 8 and 3, 7 and 4, 6 and 5 ***Note:*** *Any order is acceptable.*

Applied Problem Solving Item 10

Kareem can read 60 pages in $2\frac{1}{2}$ hours.

Correct Response

20. **Kareem can read sixty pages in two and one-half hours.** **How many pages can he read in one hour?**	24

Applied Problem Solving Item 20

Table 14

Descriptive Statistics for the KeyMath Interpreting Data subtest

Descriptives

Math Test - KeyMath Interpreting Data

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
TA	158	13.75	4.14	.32942	13.0962	14.3975	1.00	18.00
MD	69	12.03	4.28	.51531	11.0007	13.0573	0.00	18.00
RD	46	11.59	4.82	.71125	10.1544	13.0195	1.00	18.00
MDRD	87	10.28	4.77	.51174	9.2586	11.2932	0.00	18.00
Total	360	12.3028	4.61920	.24345	11.8240	12.7816	0.00	18.00

Table 15

Tukey Post-Hoc Multiple Comparisons for the KeyMath Interpreting Data subtest

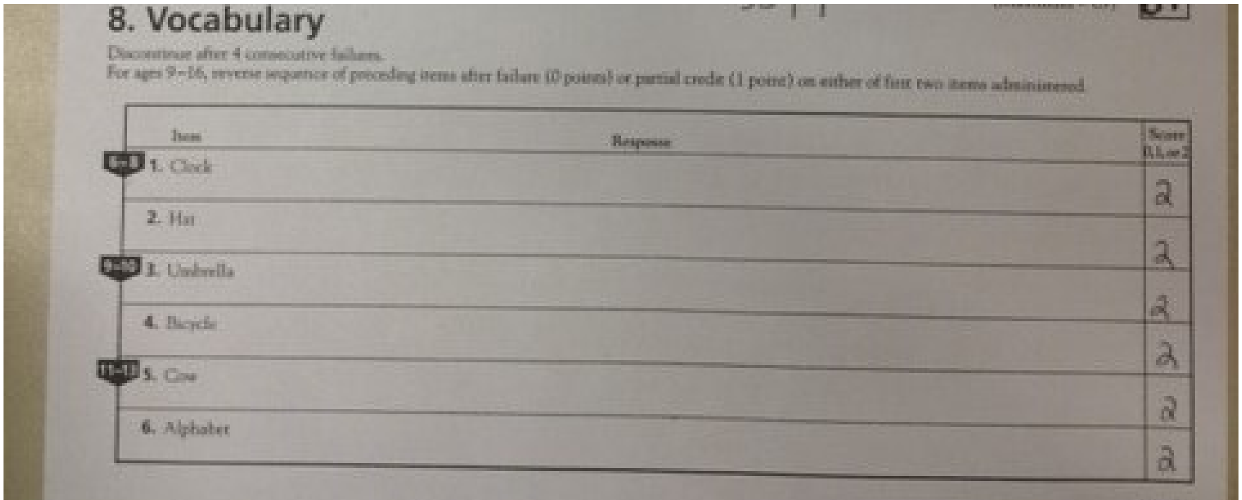
Multiple Comparisons

Dependent Variable: Math Test - KeyMath Interpreting Data
Tukey HSD

(I) Disability Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
TA	MD	1.72	.63731	.037	0.07	3.36
	RD	2.16	.73994	.019	0.25	4.07
	MDRD	3.47	.58964	.000	1.95	4.99
MD	TA	-1.72	.63731	.037	-3.36	-0.07
	RD	0.44	.84069	.953	-1.73	2.61
	MDRD	1.75	.71198	.068	-0.08	3.59
RD	TA	-2.16	.73994	.019	-4.07	-0.25
	MD	-0.44	.84069	.953	-2.61	1.73
	MDRD	1.31	.80515	.364	-0.77	3.39
MDRD	TA	-3.47097*	.58964	.000	-4.9930	-1.9490
	MD	-1.75312	.71198	.068	-3.5909	.0846
	RD	-1.31109	.80515	.364	-3.3894	.7672

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

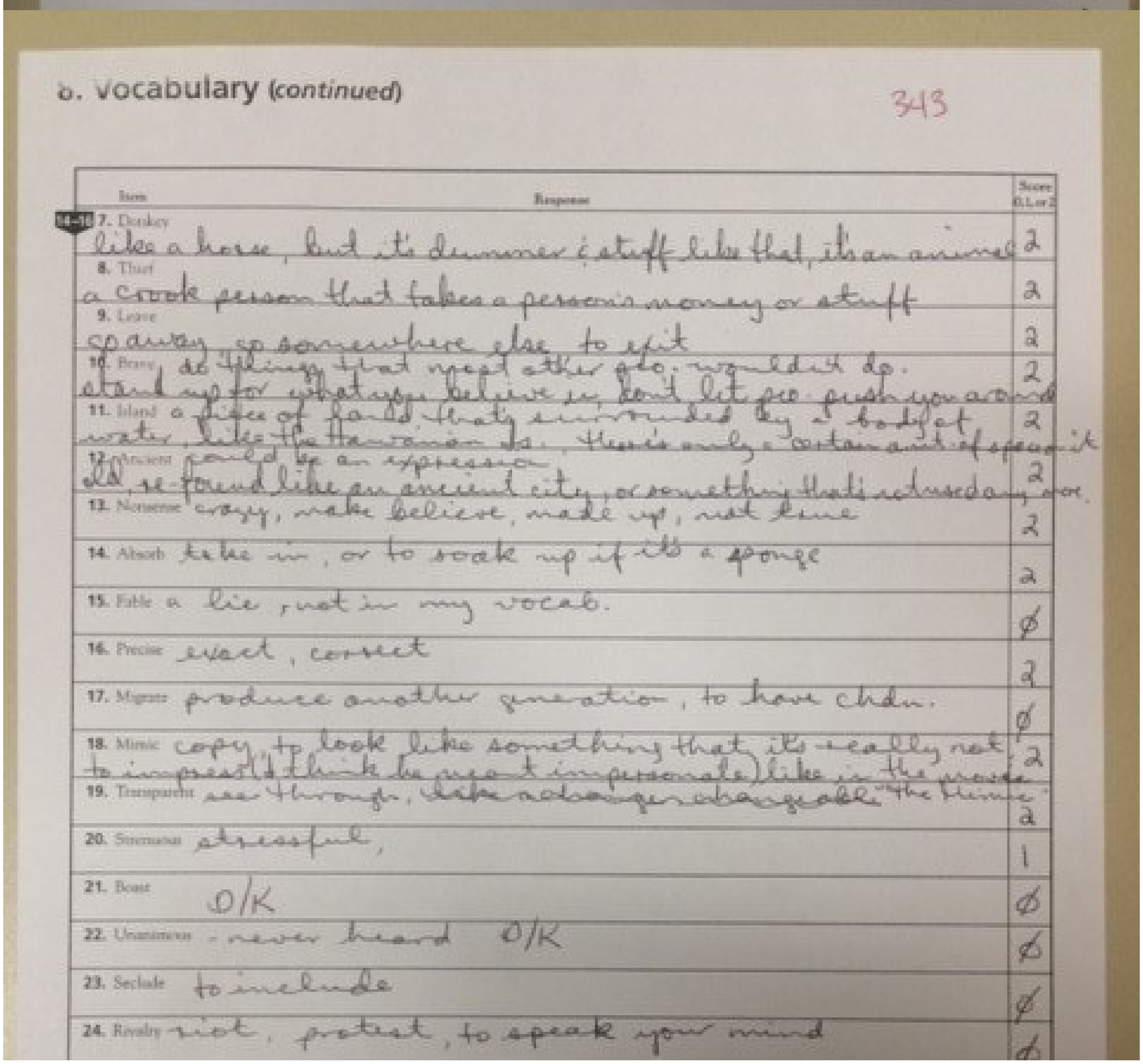
A.7 WAIS-R Vocabulary Subtest



8. Vocabulary

Discontinue after 4 consecutive failures.
For ages 9–16, reverse sequence of preceding items after failure (0 points) or partial credit (1 point) on either of first two items administered.

Item	Response	Score 0, 1, or 2
6–8 1. Clock		2
2. Hat		2
9–10 3. Umbrella		2
4. Bicycle		2
11–13 5. Cow		2
6. Alphabet		2



8. Vocabulary (continued)

343

Item	Response	Score 0, 1, or 2
14–16 7. Donkey	like a horse, but it's dummer & stuff like that, it's an animal	2
8. Thief	a crook person that takes a person's money or stuff	2
9. Leave	go away, go somewhere else, to exit	2
10. Brave	do things that most other ppl. wouldn't do. stand up for what you believe in, don't let ppl. push you around	2
11. Island	a piece of land that's surrounded by a body of water, like the Hawaiian Is. there's only a certain amt. of space, it	2
12. Ancient	could be an expression old, re-found like an ancient city, or something that's not used anymore.	2
13. Nonsense	crazy, make believe, made up, not true	2
14. Absorb	take in, or to soak up if it's a sponge	2
15. Fable	a lie, not in my vocab.	∅
16. Precise	exact, correct	2
17. Migrate	produce another generation, to have chdn.	∅
18. Mimic	copy, to look like something that it's really not to impress (I think he meant impersonate) like in the movie	2
19. Transparent	see through, ~~like not changeable~~ "the Hum[illegible]"	2
20. Strenuous	stressful,	1
21. Boast	D/K	∅
22. Unanimous	- never heard D/K	∅
23. Seclude	to include	∅
24. Rivalry	riot, protest, to speak your mind	∅

Table 16

Descriptive Statistics for the Vocabulary subtest

Descriptives

General Test 1 - WAIS-R: Vocabulary Scaled Score

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
TA	158	11.56	2.69	.21409	11.1341	11.9798	6.00	19.00
MD	69	9.61	2.47	.29792	9.0142	10.2032	1.00	16.00
RD	46	8.46	3.79	.55925	7.3301	9.5829	1.00	18.00
MDRD	87	7.22	2.47	.26486	6.6919	7.7449	1.00	12.00
Total	360	9.7389	3.28644	.17321	9.3983	10.0795	1.00	19.00

Table 17

Tukey Post-Hoc Multiple Comparisons for the Vocabulary subtest

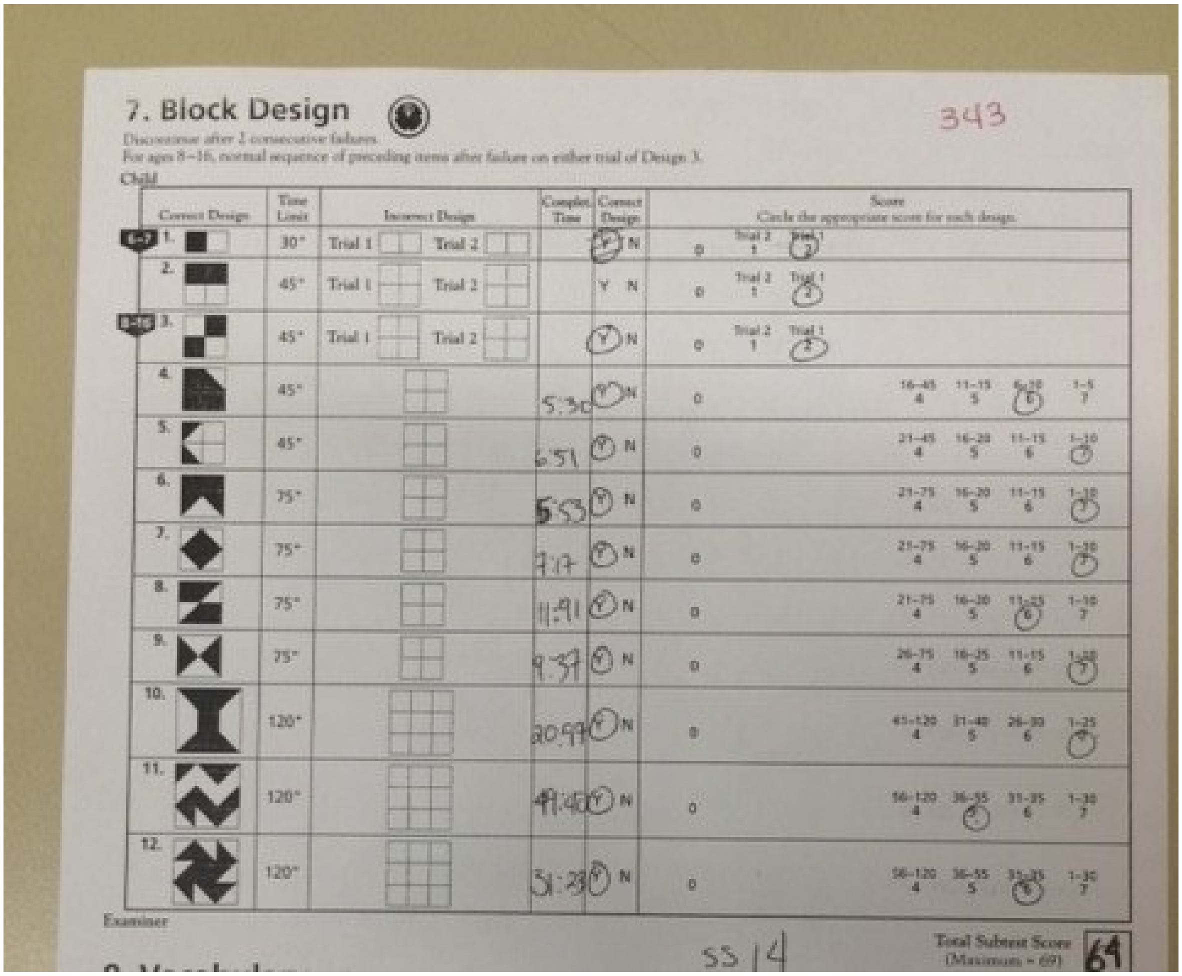
Multiple Comparisons

Dependent Variable: General Test 1 - WAIS-R: Vocabulary Scaled Score
Tukey HSD

(I) Disability Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
TA	MD	1.95	.39928	.000	0.92	2.98
	RD	3.10	.46358	.000	1.90	4.30
	MDRD	4.34	.36941	.000	3.39	5.29
MD	TA	-1.95	.39928	.000	-2.98	-0.92
	RD	1.15	.52669	.129	-0.21	2.51
	MDRD	2.39	.44606	.000	1.24	3.54
RD	TA	-3.10	.46358	.000	-4.30	-1.90
	MD	-1.15	.52669	.129	-2.51	0.21
	MDRD	1.24	.50443	.069	-0.06	2.54
MDRD	TA	-4.33857*	.36941	.000	-5.2921	-3.3850
	MD	-2.39030*	.44606	.000	-3.5417	-1.2389
	RD	-1.23813	.50443	.069	-2.5402	.0639

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

A.8 WAIS-R Block Design subtest



7. Block Design

343

Discontinue after 2 consecutive failures.
For ages 8–16, normal sequence of preceding items after failure on either trial of Design 3.

Child

Correct Design	Time Limit	Incorrect Design	Complet. Time	Correct Design	Score Circle the appropriate score for each design.				
6–7 1.	30"	Trial 1 Trial 2		Y N	0	Trial 2 1	Trial 1 2		
2.	45"	Trial 1 Trial 2		Y N	0	Trial 2 1	Trial 1 2		
8–16 3.	45"	Trial 1 Trial 2		Y N	0	Trial 2 1	Trial 1 2		
4.	45"		5:30	Y N	0	16–45 4	11–15 5	6–10 6	1–5 7
5.	45"		6:51	Y N	0	21–45 4	16–20 5	11–15 6	1–10 7
6.	75"		5:53	Y N	0	21–75 4	16–20 5	11–15 6	1–10 7
7.	75"		7:17	Y N	0	21–75 4	16–20 5	11–15 6	1–10 7
8.	75"		11:91	Y N	0	21–75 4	16–20 5	11–15 6	1–10 7
9.	75"		9:37	Y N	0	26–75 4	16–25 5	11–15 6	1–10 7
10.	120"		20:97	Y N	0	41–120 4	31–40 5	26–30 6	1–25 7
11.	120"		49:40	Y N	0	56–120 4	36–55 5	31–35 6	1–30 7
12.	120"		31:23	Y N	0	56–120 4	36–55 5	31–35 6	1–30 7

Examiner

SS 14

Total Subtest Score (Maximum = 69) 64

Table 18

Descriptive Statistics for the Block Design subtest

Descriptives

General Test 2 - WAIS-R: Block Design Scaled Score

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
TA	158	11.49	2.93	.23272	11.0277	11.9470	3.00	19.00
MD	69	8.99	2.97	.35789	8.2713	9.6997	1.00	16.00
RD	46	11.65	3.47	.51190	10.6211	12.6832	6.00	19.00
MDRD	87	8.60	3.11	.33325	7.9352	9.2602	2.00	16.00
Total	360	10.3306	3.33616	.17583	9.9848	10.6763	1.00	19.00

Table 19

Tukey Post-Hoc Multiple Comparisons for the Vocabulary subtest

Multiple Comparisons

Dependent Variable: General Test 2 - WAIS-R: Block Design Scaled Score
Tukey HSD

(I) Disability Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
TA	MD	2.50	.44052	.000	1.36	3.64
	RD	-0.16	.51146	.988	-1.49	1.16
	MDRD	2.89	.40756	.000	1.84	3.94
MD	TA	-2.50183*	.44052	.000	-3.64	-1.36
	RD	-2.67	.58109	.000	-4.17	-1.17
	MDRD	0.39	.49213	.860	-0.88	1.66
RD	TA	0.16	.51146	.988	-1.16	1.49
	MD	2.66667*	.58109	.000	1.17	4.17
	MDRD	3.05	.55653	.000	1.62	4.49
MDRD	TA	-2.88964*	.40756	.000	-3.9416	-1.8376
	MD	-.38781	.49213	.860	-1.6581	.8825
	RD	-3.05447*	.55653	.000	-4.4910	-1.6180

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

A.9 WAIS-R Digit Span subtest

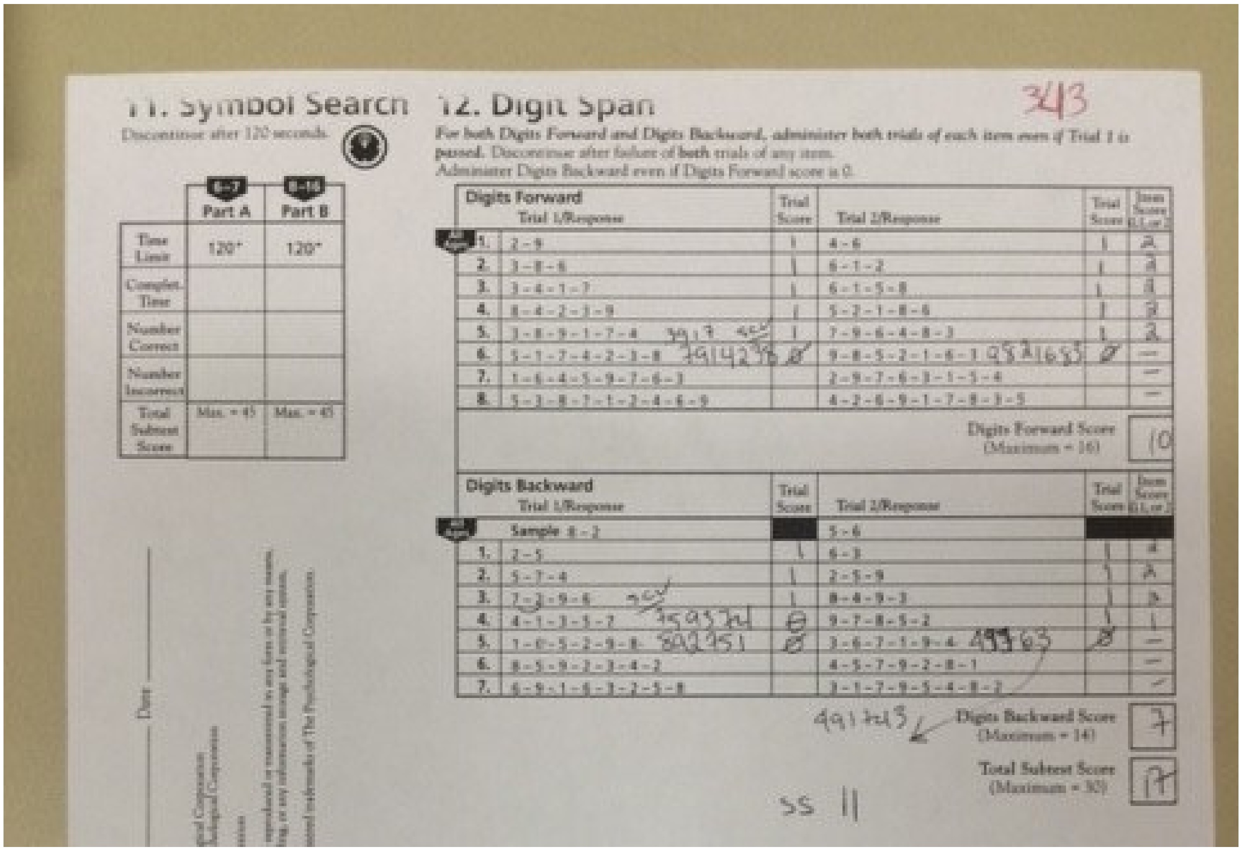


Table 20

Descriptive Statistics for the Digit Span subtest

Descriptives

General Test 3 - WAIS-R: Digit Span Scaled Score

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
TA	158	10.34	2.69	.21411	9.9125	10.7584	5.00	19.00
MD	69	8.65	2.56	.30819	8.0372	9.2672	3.00	16.00
RD	46	8.98	2.55	.37621	8.2205	9.7360	5.00	16.00
MDRD	87	6.77	2.14	.22989	6.3131	7.2271	2.00	12.00
Total	360	8.9778	2.88779	.15220	8.6785	9.2771	2.00	19.00

Table 21

Tukey Post-Hoc Multiple Comparisons for the Digit Span subtest

Multiple Comparisons

Dependent Variable: General Test 3 - WAIS-R: Digit Span Scaled Score
Tukey HSD

(I) Disability Group		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
TA	MD	1.68	.36447	0.00	0.74	2.62
	RD	1.36	.42317	0.01	0.26	2.45
	MDRD	3.57	.33721	0.00	2.69	4.44
MD	TA	-1.68327*	.36447	0.00	-2.62	-0.74
	RD	-0.33	.48079	0.91	-1.57	0.91
	MDRD	1.88	.40718	0.00	0.83	2.93
RD	TA	-1.35718*	.42317	0.01	-2.45	-0.26
	MD	0.33	.48079	0.91	-0.91	1.57
	MDRD	2.21	.46046	0.00	1.02	3.40
MDRD	TA	-3.56533*	.33721	.000	-4.4357	-2.6949
	MD	-1.88206*	.40718	.000	-2.9331	-.8310
	RD	-2.20815*	.46046	.000	-3.3967	-1.0196

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

A.10 Test Selection Criteria

	Original Database	Refined Database
Test selection	50+ psychoeducational and neuropsychological test scores, including subtests from the Woodcock- Johnson Tests of Achievement 3, Wechsler Adult Intelligence Scale, etc.	WRAT3 Arithmetic WRAT3 Reading Rosner Auditory Analysis Pseudowords Phoneme Deletion WRMT Word Attack KeyMath Interpreting Data WAIS Vocabulary WAIS Block Design WAIS Digit Span
n Participants	585 participants	360 participants
n Participants excluded	N/A	225 participants omitted: 113 participants did not complete all 9 tests, 53 participants with incomplete data, 46 participants with IQ < 70

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