THE ROLE OF ATTENTION AND WORKING MEMORY IN READING IN YOUNG ADULTS WITH A HISTORY OF READING DIFFICULTIES: MECHANISMS AND TREATMENT

by

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Table of Contents

List of Tables vii

List of Figures vii

Abstract x

List of Abbreviations Used xi

Glossary xii

Chapter 1 : Introduction 1

1.1 General Overview 1

1.1.1 Organization of the Dissertation 3

1.2 Review of Related Literature 4

1.2.1 University Students with a History of Reading Difficulties 4

1.2.1.1 Reading in University Students with HRD 6

1.2.1.1.1 Decoding 6

1.2.1.1.2 Reading Comprehension and Reading Rate 8

1.2.1.1.3 Reading Related Processes 9

1.2.1.2 Academic Performance 10

1.2.2 Posner and Colleagues' Model of Attention 11

1.2.3 Baddeley's Multicomponent Model of Working Memory 13

1.2.4 Computerized Working Memory Training 16

1.2.4.1 The N-back Task and Training. 20

1.2.4.2 WM Training and Transfer to Reading Outcomes. 21

Chapter 2 : Study 1 – Attention, working memory, and reading in undergraduate students with and without a history of reading difficulties 28

2.1 Introduction 28

2.1.1 Defining Attention and WM 28

2.1.2 HRD Students and Evidence Suggesting that Their Attention and WM May be Affected 29

2.1.2.1 Attention in Adults With Dyslexia 31

2.1.2.2 Working memory in Adults With Dyslexia. 33

2.1.3 Relationships of Reading with Attention and WM 34

2.1.4 Summary and Rationale 37

2.1.5 Study 1 39

2.2 Method 41

2.2.1 Participants. 41

2.2.2 Measures 42

2.2.2.1 Reading. 42

2.2.2.1.1 The Test of Reading Efficiency (TOWRE). 42

2.2.2.1.2 The Nelson-Denny Reading Test – Reading Comprehension (NDRT-RC) 43

2.2.2.2 Self-Reported Attention on Academic Tasks. 43

2.2.2.3 Attention and Working Memory (WM). 43

2.2.3 Procedures 44

2.3 Results 45

2.3.1 Data Cleaning 45

2.3.2 Research Question 1: What are the Reading, Attention, and WM Abilities of Individuals With a History of Reading Difficulties (HRD) Compared to Those Without (NRD)? 45

2.3.2.1 Reading. 47

2.3.2.2 Self-reported Attention on Academic Tasks. 47

2.3.2.3 Attention. 47

2.3.2.4 Working Memory 48

2.3.3 Research Question 2: Do Attention and WM Predict Decoding and Reading Comprehension? 48

2.3.3.1 Decoding 49

2.3.3.2 Reading Comprehension 50

2.4 Discussion 51

2.4.1 Characterizing Undergraduate Students With a History of Reading Difficulties 52

2.4.1.1 Reading 52

2.4.1.2 Self-Reported Attention on Academic Tasks..53
2.4.1.3 Attention 53
2.4.1.4 Working Memory 56
2.4.2 Relationships of Reading with Attention and WM. 57
2.4.2.1 Attention 57
2.4.2.2 Working Memory 58
2.4.3 Theoretical Implications 60
2.4.4 Limitations and Future Directions 61
2.4.5 Summary and Conclusions 62
Chapter 3 : Study 2 – Computerized working memory training in undergraduate students with a history of reading difficulties 83
3.1 Introduction 83
3.1.1 Summary and Rationale 88
3.1.2 Study 2 89
3.2 Methods 90
3.2.1 Participants 90
3.2.2 Measures 91
3.3.2.1 Self-Reported Attention on Academic Tasks..91
3.2.2.2 Working Memory 91
3.2.2.2.1 The Dalhousie Computerized Attention Battery (DalCAB) - Modified Version. 91
3.2.2.2.2 Operation Span Task 91
3.2.2.2.3 Reading Span Task 92
3.2.2.2.4 Symmetry Span Task 92
3.2.2.3 Reading 92
3.2.2.4 Other Measures 93
3.2.3 Training Task 93
3.2.3.1 Working Memory Training Task 94
3.2.3.2 Active Control Group Training Task 94

3.2.4 Procedures 94
3.2.4.1 Consent, Screening, and Background Characteristics 94
3.2.4.2 Pre-Training Assessment 94
3.2.4.3 Training Phase...95
3.2.4.4 Post-Training Assessment...96
3.3 Results 97
3.3.1 Data Cleaning 97
3.3.2 Is the HRD Training Sample any Different From HRD Students Who Did Not Complete Training? 97
3.3.3 Training Task Performance 98
3.3.4 Research Question: Does Dual N-back WM Training Improve WM and Reading Performance in HRD University Students?..................................100
3.3.5. Follow-Up Analyses..103
3.3.5.1 Did WM Training Progress Affect Training Outcomes? 103
3.3.5.2. Did Initial WM Ability Affect WM Training Progress? 104
3.3.5.3 Were There Differences in Group Motivation During the Training Period?..104
3.3.5.4 Were There Differences in Group Expectations for Training Effects? .105
3.4 Discussion 106
3.4.1 Limitations and Future Directions 113
3.4.2 Conclusions...115
Chapter 4 : General Discussion...135
References 145
Appendix A: Adult Reading History Questionnaire – Revised (ARHQ-R) Elementary School Scale 172
Appendix B: Summary of Research Findings on HRD University Students' Reading Skills 174
Appendix C: Description of Attention Tasks Mentioned in the Thesis, Organized Using Posner and Colleagues' Model Of Attention..............................179
Appendix D: Description of WM tasks mentioned in the thesis 181

Appendix E: Summary of Training Studies With Reading Outcomes in Child Samples 185

Appendix F: Summary of Training Studies With Reading Outcomes in Adult Samples 190

Appendix G: Screening and Background Questionnaire 192

Appendix H: Test List Order 193

Appendix I: Follow-Up Fixed Order Regression Results with Group, Attention Measures, and WM Measures as Predictors, and Decoding as the Outcome 194

Appendix J: Follow-Up Fixed Order Regression Results with Group and WM Measures as Predictors, and Reading Comprehension as the Outcome 195

Appendix K: Dalhousie Computerized Attention Battery Task Descriptions 196

Appendix M: Pre-Training Expectation Questionnaire 198

Appendix N: Pre-training Activity Questions 200

Appendix O: Post-Training Expectation Questionnaire 201

Appendix P: Bivariate Correlations Between Study 1 Participant Characteristics, Attention and Working Memory Predictors, and Reading Outcomes Across Sample of HRD and NRD Students (*n* = 102) 203

Appendix Q: Bivariate Correlations Between Study 1 Participant Characteristics, Attention and Working Memory Predictors, and Reading Outcomes in NRD students (Above Diagonal; *n* = 51) and HRD Students (Below Diagonal; *n* = 51) 204

List of Tables

Table 2.1 Demographic information of HRD (n=51) and NRD (n=51) participants......64

Table 2.2 Descriptions of Reading Measures and the Variables Used from Each Measure......65

Table 2.3 Descriptions of Attention and WM Measures and the Variables Used from Each Measure......66

Table 2.4 Performance on Assessment Measures By Group and By Factor......69

Table 2.5 Description of DalCAB Variables Used for Analyses......71

Table 2.6 Fixed Order Regression Results with Attention and WM Measures as Predictors and Decoding as the Outcome......72

Table 2.7 Fixed Order Regression Results with Attention and WM Measures as Predictors and Reading Comprehension as the Outcome......73

Table 3.1 Demographic information of WM training group and active control group participants......116

Table 3.2 Descriptions of WM Measures and the Variables Used from Each Measure......117

Table 3.3 Descriptions of Reading Measures and the Variables Used from Each Measure......120

Table 3.4 Pre-training and Post-training Performance on Assessment Measures By Training Group......121

Table 3.5 Demographic information of HRD participants who completed the training study (i.e., Trained) and those who did not (i.e., Untrained)......122

Table 3.6 Description of DalCAB Variables from Study 1 used in Study 2 Follow-up Analyses......123

Table 3.7 Regression Results for Self-Reported Attention on Academic Tasks, WM Maintenance, and WM Executive, with Training Group as the Predictor, Pre-Training Performance as a Covariate, and Post-Training Performance as the Outcome......124

Table 3.8 Regression Results for Reading Variables with Training Group as the Predictor, Pre-Training Performance as a Covariate, and Post-Training Performance as the Outcome......125

Table 3.9 Description of Expectation Rating Composites/Categories......126

List of Figures

Figure 2-1 Forest plots of Cohen’s d for the reading variables and factor....................74

Figure 2-2 Forest plots of Cohen’s d for the vigilance processing speed variables and factor 75

Figure 2-3 Forest plots of Cohen’s d for the vigilance decision speed variables and factor...76

Figure 2-4 Forest plots of Cohen’s d for the orienting variables and factor..................77

Figure 2-5 Forest plots of Cohen’s d for the attentional control: switching/shifting variables and factor..78

Figure 2-6 Forest plots of Cohen’s d for the attentional control: interference control/conflict resolution variables and factor..79

Figure 2-7 Forest plots of Cohen’s d for the attentional control: inhibiting variables and factor 80

Figure 2-8 Forest plots of Cohen’s d for the working memory maintenance variables and factor 81

Figure 2-9 Forest plots of Cohen’s d for the working memory control variables and factor...82

Figure 3-1 CONSORT flow chart 127

Figure 3-2 Forest plots of Cohen’s d for factors of WM maintenance, WM executive, and reading between HRD participants who did and did not complete the training study...128

Figure 3-3 Individual performance on the WM training task: Average n-level achieved by session 129

Figure 3-4 Individual performance on the active control task: Average reaction time achieved by session 129

Figure 3-5 Individual performance on the active control task: Average accuracy achieved by session 131

Figure 3-6 Forest plots of beta (B) for training group as a predictor of post-training performance on the outcome variables from the self-report measure of attention on academic tasks, working memory maintenance measures, and WM executive measures, with pre-training performance as a covariate 132

Figure 3-7 Forest plots of beta (B) for training group as a predictor of post-training performance on the outcome variables from the reading measures with pre-training performance as a covariate......133

Figure 3-8 Adjusted mean differences by factor calculated from linear mixed models......134

Abstract

University students with a history of reading difficulties (HRD) have ongoing reading and academic challenges. Understanding the mechanisms underlying these students' reading difficulties and identifying ways to improve their reading performance is critical given the importance of reading to academic achievement. Given the empirical evidence and conceptual rationale for the role of attention and working memory (WM) in reading, in Study 1 I investigated these abilities and their relationships with reading in 51 HRD students in comparison to 51 university students without a history of reading difficulties (NRD). Relative to their NRD peers, HRD students demonstrated weaknesses on measures of decoding, reading comprehension, vigilance decision speed, orienting attention, and response inhibition, as well as on verbal and visuospatial WM measures that involve attentional control (i.e., WM executive tasks). Verbal WM was significantly related to reading performance in NRD students, consistent with previous research in normal adult readers. In contrast, both verbal and visuospatial WM were related to reading in the HRD group. These findings indicated that an intervention aimed at improving WM may be one avenue for improving HRD students' reading skills. Based on the findings from Study 1 and given the empirical evidence and theoretical rationale for training WM to improve reading performance, in Study 2 I evaluated the effectiveness of 10 sessions of training on an adaptive dual *n*-back task versus training on an active control task at improving their WM and reading performance. HRD participants made smaller gains on the adaptive WM training task than expected, with no evidence of transfer to untrained WM and reading measures. The findings of this dissertation demonstrate that HRD students have weaknesses in attention and WM relative to NRD students, that may be similar to those previously identified in adults with dyslexia and that may contribute to their reading difficulties. The findings also suggest that training HRD students on an adaptive dual *n*-back training task may not improve their WM and reading functions. Ways in which training gains and transfer could have been influenced by intervention-specific features, individual characteristics, and theorized mechanisms of transfer are discussed.

List of Abbreviations Used

ARHQ-R	Adult Reading History Questionnaire-Revised
ConjS	Conjunction Search (search type on the DalCAB Visual Search test)
CRT	Choice Reaction Time (DalCAB subtest)
DalCAB	Dalhousie Computerized Attention Battery
DT	Dual-Task (DalCAB subtest)
FA	False Alarm
FeatS	Feature Search
Flanker Int	Flanker Interference (score on the DalCAB Vertical Flanker test)
GNG	Go/No-Go (DalCAB subtest)
HRD	History of Reading Difficulties
IM	Item Memory (DalCAB subtest)
LASSI-Conc	Learning and Studying Strategies Inventory: Concentration Subscale
LD	Learning Disability
LM	Location Memory (DalCAB subtest)
NDRT-RC	Nelson-Denny Reading Test - Reading Comprehension subtest
NRD	No History of Reading Difficulties
RT	Reaction Time
SRT	Simple Reaction Time (DalCAB subtest)
TOWRE	Test of Reading Efficiency
TOWRE PDE	Phonemic Decoding Efficiency subtest of the TOWRE
TOWRE SWE	Single Word Efficiency subtest TOWRE
VSSP	Visuospatial Sketchpad
WM	Working Memory

Glossary

Attentional Control: Involves the deployment, coordination, and regulation of attentional resources (Fernandez-Duque & Posner, 2001). Another term for executive control of attention.

Decoding: Reading of written words and non-words with accuracy and/or fluency

Dyslexia: A neurobiological and developmental learning disability primarily characterized by difficulties in reading and spelling (Roitsch & Watson, 2019)

Far Transfer: Gains on measures that are thought to involve the process(es) trained by a cognitive intervention but that are not direct measures of the trained process(es).

Learning Disabilities: neurodevelopmental disorders that are characterized by persistent difficulties in reading, written expression, and/or mathematics (American Psychiatric Association, 2013)

Morphological Awareness: Ability to recognize and consciously manipulate the smallest units of meaning in language (i.e., morphemes)

Near Transfer: Improvements on tasks assessing processes trained by a cognitive intervention that have “different stimulus materials and/or task structure” (von Bastian et al., in press, p. 4) than the training task.

Orienting Attention: involves selecting and directing one’s attention to a stimulus or location in the environment in order to process it more fully (Fernandez-Duque & Posner, 2001)

Orthographic Processing: “[A]bility to form, store, and access orthographic representations” (Cunningham et al., 2011, p. 263)

Phonological Awareness: Ability to recognize and consciously manipulate sounds in language

Phonological Memory: Ability to maintain and recall speech-based sounds in temporary memory stores

Pseudowords: Letter strings that are orthographically and phonologically legal in a certain language, but do not have a meaning

Reading Comprehension: “[T]he process of simultaneously constructing and extracting meaning through interaction and engagement with written language” (RAND Reading Study Group, 2002, p. 11)

Response Inhibition: Active suppression of dominant, automatic, or especially powerful responses to stimuli in the environment

Reading Rate: The speed at which an individual reads connected text (i.e., multiple related sentences)

Shifting/Switching Attention: “[F]lexibly shift[ing] attention between mental sets, operations, or tasks” (Butterfuss & Kendeou, 2017, p. 2).

Vigilance/Alerting Attention: The ability to initiate and maintain a mental state of readiness leading to the ability to quickly detect, select, and respond to relevant stimuli (Fernandez-Duque & Posner, 2001).

Working Memory Control: : In reference to the domain-general attentional control system of working memory

Working Memory Maintenance: In reference to the domain-specific storage systems of working memory

Chapter 1: Introduction

1.1 General Overview

The number of students with learning disabilities (LD) attending post-secondary institutions has been increasing over that last several decades (Henderson, 2001; Learning Disabilities Association of Ontario, 2018; Nichols et al., 2002). LDs refer to neurodevelopmental disorders that are characterized by persistent difficulties in reading, written expression, and/or mathematics (American Psychiatric Association, 2013). Although it is not known what proportion of students in post-secondary institutions in Canada have learning disabilities, it is estimated that approximately 2–5% of Canadian college and university students, most of which present with diagnoses of LD and/or ADHD, register with their schools' disability service offices (Harrison & Wolforth, 2012). Legislation passed by Canadian provinces (e.g., Nova Scotia, Ontario, and Alberta; Alberta Human Rights Commission, 2021; *Human Rights Act*, 1989; Post-Secondary Accessibility Working Group, 2020) and in other countries (e.g., Israel, United Kingdom, and United States of America; (*Americans With Disabilities Act of 1990*, 1990; *Equality Act*, 1989; *Israel: Law on Rights of Students with Learning Disabilities Amended*, 2014) entitle students with documented disabilities to access supports, accommodations, and services to promote equitable opportunity in post-secondary education.

Whereas university students with documented LDs can access academic supports tailored to their needs, there remains a substantial portion of university students who are potentially academically vulnerable who do not have access to disability services. One such group, university students who have a history of reading difficulties (HRD), has gained increasing attention over recent years. They make up as high 10% to 30% of undergraduate students (HRD; Bergey et al., 2017; Chevalier et al., 2017; Deacon et al., 2017). These students, even at the university level, have similar reading and phonological challenges as their peers with diagnosed learning disabilities (Deacon et al., 2012). Although many HRD students are able to sufficiently compensate for their problems in order to cope with the demands of elementary and secondary education, and gain admission to university, they experience significant academic challenges at the post-secondary level (Bergey et al., 2017; Chevalier et al., 2017; Deacon et al., 2017). Since only a minority of HRD university students have a documented diagnosis of an LD (i.e., probably fewer than 20%; Bergey et al., 2018; Deacon et al., 2012), many do not have access to the supports and services provided to those with documented disabilities. As a potential consequence, HRD students have been found to achieve lower first-year GPAs than their peers without histories of reading difficulties (Bergey et al., 2017; Chevalier et al., 2017), whereas students with LDs who receive supports tailored to their learning needs achieve similar or better GPAs than their peers without LDs (Hen & Goroshit, 2014; Sarid et al., 2020).

In recent years, there has been growing body of literature aimed at better understanding the challenges faced by HRD students in the university setting and identifying ways to support them with the goal of improving their academic outcomes. Contrasted with NRD students, previous studies have investigated HRD students' academic skills and related language and literacy processes (e.g., Deacon et al., 2012; MacKay et al., 2019; Metsala et al., 2019), their use of metacognitive reading and study strategies (Bergey et al., 2017; Chevalier et al., 2017), their academic motivations (Bergey et al., 2018), and their psychological functioning (Elgendi et al., 2021). Furthermore, researchers have begun to explore ways of directly supporting these students through personalized outreach for academic support services available to all students (Deacon et al., 2017) and study strategy intervention (Bergey et al., 2019).

The first aim of this thesis was to better understand the underlying cognitive mechanisms of HRD university students' reading difficulties. Previous research suggests that higher-order cognitive skills, such as attention and working memory (WM), are likely involved in and important for reading development and performance. Longitudinal studies have found evidence for the involvement of WM and attention behaviours in the growth of reading skills (Larsen et al., 2022; Morgan et al., 2019; Stipek & Valentino, 2015; Swanson & Jerman, 2007). Moreover, cross-sectional studies have found positive associations between reading performance and WM and attention abilities in children and adults (e.g., De Beni et al., 2007; Follmer, 2018; Hannon, 2012; Ober et al., 2020; Peng et al., 2018). Further, WM deficits have been identified as common features in the cognitive profiles of adults with dyslexia (e.g., Ghani & Gathercole, 2013; Smith-Spark

& Fisk, 2007; Vasic et al., 2008). Given empirical support for the involvement of attention and WM in reading, it is possible that attention and WM processes may be partially responsible for HRD students' weaknesses in reading skills, relative to their NRD peers. Thus, Study 1 of this thesis investigated the reading, attention, and WM abilities of a sample of HRD university students compared to a sample of NRD university students, and the relationships of attention and WM abilities with reading performance.

The second aim of this thesis was to identify an effective way of supporting HRD students in academic settings. Based on findings from Study 1 in support of the potential involvement of WM in HRD students' reading performance, this thesis specifically looked at whether remediation aimed at WM is effective in improving HRD students' WM and reading abilities. Computerized WM training typically involves the intensive, repetitive practice of adaptive WM tasks, with the intended outcome of improving performance on untrained WM tasks (i.e., near transfer) and/or on measures of abilities involving WM processes (i.e., far transfer). Gains on untrained tasks following WM training are hypothesized to occur as the result of an increase in WM capacity, an enhanced efficiency of using available WM resources (von Bastian et al., in press; von Bastian & Oberauer, 2014), and/or the development of new relevant cognitive routines that can be applied to other tasks (Gathercole et al., 2019). Previous research has found evidence for gains in reading performance following WM training, with the strongest support for gains in reading comprehension of passages (e.g., Artuso et al., 2019; Chein & Morrison, 2010; K. I. E. Dahlin, 2011; Egeland et al., 2013; Henry et al., 2014). Given the potential for WM training to improve reading performance, it may be an effective intervention tool for HRD students in the university setting. Thus, Study 2 of this thesis evaluated the effectiveness of a WM training program in improving WM and reading performance in a subset of the sample of HRD participants from Study 1.

1.1.1 Organization of the Dissertation

The remainder of this chapter provides a review of topics important for the contextualization of the dissertation and the details presented in subsequent chapters of the thesis. First, HRD students' reading and academic challenges, and their self-reported cognitive challenges are reviewed. Subsequently, models used to inform my investigations of attentional abilities (i.e., Posner and colleagues' model of attention;

Petersen & Posner, 2012) and WM function (i.e., Baddeley's (2012) multicomponent model of WM) are described. Finally, an overview of approaches to WM training is provided, with a focus on *n*-back training, the type of training task implemented in Study 2 of this dissertation (see description below). Chapter 1 ends with a review of previous studies that investigated the effects of WM training on reading outcomes in impaired adult readers, adults diagnosed with ADHD and/or LD, and typically developing adults. Chapters 2 and 3 describe Study 1 and Study 2, respectively. The fourth and final chapter summarizes the findings from Study 1 and 2, discusses the implications of the findings and suggested directions for future research. As Study 1 and 2 were prepared as independent manuscripts to be submitted for subsequent publication, there is some overlap of information amongst the chapters.

1.2 Review of Related Literature

1.2.1 University Students with a History of Reading Difficulties

In most cases, children who have difficulties with reading acquisition go on to have continued deficits in reading and spelling during adulthood (see Bruck, 1998 for review). In some cases, students with early reading difficulties will compensate well enough for those difficulties to cope effectively with the academic demands of primary and secondary education, despite lower reading and spelling skills than their peers without childhood LDs and without a history of reading difficulties (NRD; Lefly & Pennington, 1991; McGonnell et al., 2007; Parrila et al., 2007). These individuals may be more likely to achieve higher levels of education than their peers with childhood diagnosed reading-specific LDs who are unable to effectively compensate for their reading and/or spelling deficits (Lefly & Pennington, 1991). This unique population of students with childhood reading problems in post-secondary institutions have been described previously as *high-functioning dyslexics* (e.g., Deacon et al., 2012; Kemp et al., 2009) or *university students with a history of reading difficulties* (HRD students; e.g., Bergey et al., 2017; Deacon et al., 2012; Elgendi et al., 2021).

HRD students are typically defined as university students who self-report having had reading difficulties in childhood (e.g., Bergey et al., 2018; Deacon et al., 2012; Kemp et al., 2009, p. 20; Parrila et al., 2007). The self-report questionnaire most commonly used by researchers to identify adults with HRD and with no history of reading difficulties (NRD) is the Elementary School Scale of the Adult Reading History Questionnaire – Revised (ARHQ-R; Parrila et al., 2003; Appendix A). This scale consists of eight items that ask respondents about their reading and spelling performance, reading attitudes, reading speed, additional help received for reading, and exposure to reading in elementary school. Each item requires a response on a 5-point Likert-like scale (i.e., 0 to 4) with high scores indicative of greater reading difficulty or less reading exposure. Proportion scores ranging from a low of 0 to high of 1 can be calculated by dividing respondents total scores across the eight items by the maximum possible total (i.e., 32), with higher scores reflective of more difficulty with reading in elementary school. To classify respondents' reading histories, researchers have used cut-offs with proportion scores between 0 and .25 classified as NRD and scores of .37 and greater as HRD (e.g., Bergey et al., 2017; Deacon et al., 2012). Respondents with proportion scores between .25 and .37 are not classified as either HRD or NRD. Using these criteria to define university students with HRD and NRD, researchers have found that those with HRD have lower levels of current reading ability and lower academic performance than their NRD peers (e.g., Bergey et al., 2017; Deacon et al., 2012).

A more restrictive approach to identifying students with childhood reading problems in post-secondary institutions for research studies is to require a recent or childhood diagnosis of dyslexia – a neurobiological and developmental learning disability primarily characterized by difficulties in reading and spelling (Gallagher et al., 1996; Miller-Shaul, 2005; Roitsch & Watson, 2019; Sebastian & Yasin, 2008). Although this approach ensures that research participants either had or have objective problems in reading, it fails to capture a portion of university students with early reading difficulties who did not obtain a diagnosis of dyslexia in childhood or who are not assessed for or continue to meet criteria for an LD in adulthood (Lefly & Pennington, 1991; McGonnell et al., 2007; Parrila et al., 2007). Using the ARHQ-R to identify HRD and NRD students, researchers have found that only a minority of HRD students have documented LD diagnoses either in childhood or as adults (e.g., 14.3% in McGonnell et al., 2007; 19% in Deacon et al., 2012; and 18% in Bergey et al., 2018). Despite the low rate of LD diagnoses in HRD students, little differences in the reading abilities of university students who self-report HRD and those with recently diagnosed LDs have been found. Given that the self-report approach (e.g., using the ARHQ-R) captures a wider range of HRD university students with ongoing weaknesses in reading, it is likely to result in a more representative sample and more practically relevant and ecologically valid findings. For this reason, the ARHQ-R is used to recruit and classify HRD and NRD participants for this thesis.

1.2.1.1 Reading in University Students with HRD. See Appendix B for a summary of studies that have evaluated HRD university students' reading skills compared to their NRD peers and university students with documented LDs or dyslexia.

1.2.1.1.1 Decoding. Decoding is the ability to read written words and non-words with accuracy and/or fluency (e.g., Melby-Lervåg & Lervåg, 2014; Peng et al., 2018). It is believed to involve the use of grapheme-phoneme-correspondence knowledge (i.e., knowledge of single letter/digraph representations of the smallest units of sounds in language) and orthographic knowledge (i.e., the knowledge of written representations of spoken language) to decipher written text (Apel et al., 2019; Ehri, 2014; Querido et al., 2021). Decoding skills are typically measured using untimed or timed tests wherein individuals are asked to accurately read lists of single words or pseudowords.

HRD students have demonstrated weaknesses in untimed decoding skills relative to their NRD peers. Most studies evaluating the untimed word and pseudoword reading skills of HRD students have used the Word Identification and Word Attack subtests from the Woodcock Reading Mastery Test-Revised (WRMT-R; Woodcock, 1987, 1998). The subtests involve reading a list of increasingly more difficult words or pseudowords, respectively. Performance is measured based on the number of correctly read items. HRD students have demonstrated, on average, grade equivalent performance between grades 11 and 12 on the Word Identification subtest, reflecting approximately three to five grade levels below their NRD peers (Deacon et al., 2006, 2012; Parrila et al., 2007). They have also demonstrated, on average, performance on the Word Attack subtests at a grade seven level (Deacon et al., 2006; Parrila et al., 2007), approximately five grade levels below their NRD peers (Parrila et al., 2007). Based on guidelines proposed by Cohen (1969; i.e., d = 0.20, 0.50, 0.80 for small, medium, and large effects respectively), effect size estimates of the group differences have been found to be consistently large on both the Word Identification subtest (ds ranging from 0.99 to 1.59) and the Word Attack subtest (*d*s ranging from 1.12–1.33; Deacon et al., 2006, 2012; Kemp et al., 2009; McGonnell et al., 2007; Parrila et al., 2007). Parrila et al. (2007) found similarly large group differences between HRD and NRD students on Castles and Coltheart's (1993) reading test which involves reading a list of 90 items made up equally of regular words, irregular words, and pseudowords. Although both groups' accuracies for regular words were at ceiling, HRD students were significantly less accurate than their NRD peers for irregular words (d = 0.80) and pseudowords (d = 1.24). Without time pressure, HRD students have thus consistently demonstrated, across multiple measures, poorer decoding skills than their NRD peers.

HRD students have also demonstrated weaknesses in decoding skills on timed tasks that place emphasis on both speed and accuracy of reading. Most studies evaluating the timed word and pseudoword reading skills of HRD students have used the Single Word Efficiency and Phonemic Decoding Efficiency subtests from the Test of Reading Efficiency (TOWRE; Torgesen et al., 1999). Respectively, the subtests involve trying to correctly read as many words or pseudoword as possible in 45 seconds. HRD students have been found to read fewer items correctly within the allotted time than their NRD peers, with small to large effects on the Single Word Efficiency subtest (*d*s ranging from 0.43 to 0.91) and medium to large effects on the Phonemic Decoding Efficiency subtest (*d*s ranging from 0.99 to 1.59; Deacon et al., 2012; Hebert et al., 2018; MacKay et al., 2019; Metsala et al., 2019). HRD students show, on average, grade equivalent performance between grades 9.5 and 10.5 on the Single Word Efficiency subtest, about one to two grade levels below their NRD peers (Deacon et al., 2012; Hebert et al., 2018; MacKay et al., 2019; Metsala et al., 2019). On average, HRD performance on the Phonemic Decoding Efficiency subtest is between the eighth and ninth grade level, approximately 3.5 to 4.5 grade levels below their NRD peers (Deacon et al., 2012; Hebert et al., 2018; Metsala et al., 2019; but see MacKay et al., 2019). Thus, perhaps not surprisingly, HRD students' weaknesses in accurate word and pseudoword reading extend to measures wherein both speed and accuracy are emphasized.

HRD university students' weaknesses in reading have been shown to be similar to their peers with documented LDs. Deacon et al. (2012) compared the performance of HRD and NRD university students to a sample of university students with a recently documented LD or diagnosis of dyslexia on the WRMT-R Word Identification subtest and the TOWRE subtests. The NRD group performed better than both the HRD and LD groups on all three measures. Especially notable, there were no differences between the HRD and LD groups on any of the decoding measures. Thus, HRD students have been found to have difficulties in decoding skills similar to their peers with known learning deficits.

1.2.1.1.2 Reading Comprehension and Reading Rate. Reading comprehension is "[...]the process of simultaneously constructing and extracting meaning through interaction and engagement with written language" (RAND Reading Study Group, 2002, p. 11). Studies evaluating the reading comprehension and reading rate skills of HRD students have used the Nelson-Denny Reading Test – Reading Comprehension subtest (NDRT-RC**).** The NDRT-RC involves reading five short passages and responding to factual and inferential multiple-choice questions about the passages during a period of 20 minutes (Brown et al., 1993). Two measures from the NDRT-RC include timed reading comprehension (the total number of correct response within the 20 minutes), and untimed-reading comprehension (the percentage of correct responses of the items attempted within the time limit; e.g., Deacon et al., 2006, 2012; MacKay et al., 2019). Reading rate is determined based on how much of the first passage is read during the first minute of the test.

HRD students have demonstrated weaknesses in *timed* reading comprehension. They have been found to get fewer comprehension questions correct than their NRD peers within the 20–minute time limit of the NDRT-RC, with *d*s ranging from 0.73 to 1.44 (Corkett et al., 2006; Deacon et al., 2006, 2012; Kemp et al., 2009; MacKay et al., 2019; McGonnell et al., 2007; Metsala et al., 2019; Parrila et al., 2007). They have also been found to perform similarly to university students with documented LDs or dyslexia on the same measure (Deacon et al., 2012). Deacon et al. (2012) also reported that HRD and LD students have, on average, eleventh grade *timed* reading comprehension abilities, approximately four grade levels below their NRD peers. Thus, HRD have demonstrated timed reading comprehension abilities similar to their peers with known learning deficits and worse than their NRD peers.

Notably, however, estimates of *timed* reading comprehension grade equivalence have varied, and group differences in *untimed* reading comprehension have not been consistently shown. In some studies, HRD group *timed* reading comprehension performance, although still significantly lower than their NRD peers, has been found to be at approximately the 2nd year university level, on average (Deacon et al., 2006; Kemp et al., 2009; Parrila et al., 2007). In the same studies, there were no group differences between HRD and NRD students in *untimed* reading comprehension. In contrast, other studies have found that HRD students' *timed* reading comprehension was, on average, at the upper high school level (i.e., approximately the eleventh to twelfth grades) with worse *timed* and *untimed* reading comprehension than their NRD peers (Deacon et al., 2012; MacKay et al., 2019; McGonnell et al., 2007; Metsala et al., 2019). In those studies, effect sizes of significant group differences in *untimed* reading comprehension ranged from medium to large (*d*s ranging from 0.72 to 1.33). These varying results are likely reflective of the heterogeneity of HRD students in the university setting, presenting with reading comprehension skills along a continuum of performance.

Interestingly, Deacon et al. (2012) identified reading performance patterns that differentiated HRD students from a sample of university students with documented LDs or dyslexia. First, although both the HRD and LD participants in their study had slower reading rates than NRD students (*ds* = 1.33), HRD students read at a significantly faster rate than their LD peers (*d* = 1.16), but with lower untimed reading comprehension. In contrast, whereas the LD group's reading rate was slower than the HRD group, their untimed reading comprehension was equivalent to NRD group. Although faster reading rates have previously been associated with better reading comprehension in typically developing readers, the optimal reading rate for effective reading comprehension in less skilled readers may be slower than in skilled readers (O'Connor, 2018). The authors suggested that this pattern of results might reflect differences in reading strategy between the HRD and LD groups, with the former prioritizing reading speed over reading comprehension, and the latter taking the opposite approach.

1.2.1.1.3 Reading Related Processes. Researchers have also investigated language and literacy-related processes in HRD university students that may be associated with their reading difficulties. A detailed review of that literature is beyond the scope of this dissertation; however, in summary, HRD university students have demonstrated similar phonological awareness abilities than their peers diagnosed with LDs (Deacon et al., 2012), and weaker phonological awareness, phonological memory, morphological awareness, and orthographic processing abilities than their NRD peers (e.g., Al Dahhan et al., 2014; Deacon et al., 2012; Metsala et al., 2019; Parrila et al., 2007). Further, HRD students have been found to be significantly slower than their NRD peers at rapid automatic naming (Al Dahhan et al., 2014; Corkett et al., 2006; Kemp et al., 2009; Parrila et al., 2007), the ability to quickly name highly familiar stimuli. RAN performance requires the coordination of perceptual, motoric, and linguistic processes, as well as cognitive processes such as attention and working memory (WM; Arnell et al., 2009; Wolf & Bowers, 1999).

1.2.1.2 Academic Performance. In addition to reading-related difficulties, HRD university students have also been identified as an academically vulnerable group. In a study of 244 HRD and 603 NRD first year students, Bergey et al. (2017) found that although HRD students attempted the same number of first year credits as their NRD peers, HRD students completed fewer credits, failing or dropping out of an average of one course during their first year. Further, Bergey et al. found that HRD university students achieved a lower cumulative first-year grade point averages (GPA) than their NRD peers. Similarly, Chevalier et al. (2017) evaluated group differences in GPA of 77 HRD and 295 NRD first-year university students. They found that HRD students achieved a significantly lower first-year GPA than their NRD peers. Chevalier et al. and Bergey et al.’s findings are notable in contrast to research from the last two decades showing that students with diagnosed LDs earn similar GPAs as their peers without LDs (Heiman & Precel, 2003; Sarid et al., 2020). Importantly, Sarid et al. (2020) found that although graduates with LDs from a postsecondary institution in Israel (n = 315) entered their programs with lower admission scores than their peers without LDs (n = 955), they achieved higher GPAs than their no LD peers. Regardless of their admissions scores, Sarid et al. found that academic supports for graduates with LDs seemed to contribute to their academic success. Although Sarid et al.’s study was not conducted in Canada, the country where the current thesis project was carried out, it provides compelling evidence suggesting that postsecondary students with learning needs can benefit greatly from academic accommodations and support services. Unfortunately, as the majority of HRD students do not have a formal diagnosis of a LD, they do not have access to the same supports as their diagnosed peers to overcome their academic difficulties.

1.2.2 Posner and Colleagues' Model of Attention

Attention and working memory will be a focus of this thesis, thus a review of models is provided. Attention is both a form of alertness as well as a mechanism of resource allocation (Raz & Buhle, 2006), selectively prioritizing sensory information for the purpose of directing focus to the most important stimuli (Carrasco, 2011). Posner and colleagues proposed a framework of the attention system that has been supported with neuroimaging data; it consists of distinct brain networks responsible for three attentional components: vigilance/alerting, orienting, and executive control (Fan et al., 2002, 2005; Fernandez-Duque & Posner, 2001; Petersen & Posner, 2012; Posner & Petersen, 1990). Although the networks of attention have been found to be anatomically and functionally separate, they can interact and modulate one another for optimal performance (Callejas et al., 2005; Fan et al., 2009). Petersen and Posner's (2012) most recent update to their original framework of attention (Posner & Petersen, 1990) is described below. See Appendix C for a description of attention task paradigms mentioned in this thesis. The listed tasks and upcoming reviews of research on attention in dyslexia are organized using Posner's model of attention. Note that the literature review in Chapter 2 (i.e., the introduction for Study 1) includes the citations listed in the appendix.

Vigilance/alerting is the ability to initiate and maintain a mental state of readiness leading to the ability to quickly detect, select, and respond to relevant stimuli (Fernandez-Duque & Posner, 2001). This component can be measured using warning signal tasks that evaluate phasic alertness (i.e., rapid change in alertness in response to an external event), and simple reaction time, choice reaction time, and continuous performance tasks that evaluate tonic alertness/vigilance (i.e., intrinsic alertness; Fernandez-Duque & Posner, 2001; Nicolson & Fawcett, 1994; Petersen & Posner, 2012). Vigilance/alerting has been associated with the neuromodulator norepinephrine and the frontal, parietal, and thalamic regions of the brain (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Petersen & Posner, 2012), and matures throughout infancy, childhood, and adolescence (Morandini et al., 2020; Pozuelos et al., 2014; Rueda & Posner, 2013).

Orienting involves selecting and directing one's attention to a stimulus or location in the environment in order to process it more fully (Fernandez-Duque & Posner, 2001). This process requires disengagement from the current focus, attentional movement, and reengagement of focus on the new stimulus/location of interest. Attentional orienting is typically measured using visual tasks, including spatial cuing tasks and visual search tasks. Within the visual domain, orienting can be overt, involving the movement of the eyes and/or head towards the stimulus/location of interest, or covert, involving no movement of the eyes or head. The attentional orienting system has been associated with the neuromodulator acetylcholine and is made up of two distinct but interacting brain networks: (1) a bilateral dorsal system related to strategic control over attention and (2) a strongly right-lateralized ventral system related to breaking the current focus of attention to allow attention to be focused on a new stimulus (Corbetta & Shulman, 2002; Petersen and Posner, 2012). Orienting matures beginning in infancy, typically reaching adult-like levels by middle childhood (see Rueda & Posner, 2013 for review).

Lastly, *executive control* of attention (here after referred to as attentional control), involves the deployment, coordination, and regulation of attentional resources (Fernandez-Duque & Posner, 2001). It is important for many functions including but not limited to set maintenance, error detection, conflict monitoring and resolution, and component executive functions (i.e., inhibition, switching/shifting, and updating; Miyake et al., 2000) and WM (Callejas et al., 2005; Fernandez-Duque & Posner, 2001; Kar & Kenderla, 2017; Petersen & Posner, 2012). Attentional control is often assessed with measures of inhibition, switching/shifting, and updating (Callejas et al., 2005; Fernandez-Duque & Posner, 2001; Kar & Kenderla, 2017; Petersen & Posner, 2012). These measures are believed to share attentional control as an underlying component (McCabe et al., 2010) such as measures of interference control/conflict resolution (e.g., Flanker tasks, Stroop tasks, Simon tasks), response inhibition (e.g., Stop-signal tasks and go/no-go tasks) and task switching (e.g., Plus minus task).The attentional control system has been associated with two relatively distinct networks: (1) a frontoparietal system, separate from the orienting system, thought to be associated with task initiation, switching, and within-trial real-time adjustments, and (2) a cingulo-opercular system associated with maintenance across trials and for overall task performance (Peterson &

Posner, 2012). Earliest evidence of the attentional control component of attention is around seven months. Maturation of the associated networks occurs throughout childhood (Best & Miller, 2010; Pozuelos et al., 2014; Rueda & Posner, 2013) and continues into adolescence (Best & Miller, 2010; Crone et al., 2018; Morandini et al., 2020; Waszak et al., 2010).

In Chapter 2 of this thesis, I investigate the functioning of the three attentional components of attention in HRD students, in contrast to their NRD peers. Further, I evaluate their combined and unique associations with decoding and reading comprehension performance in HRD and NRD students. To evaluate the three components of attention, I use measures of tonic alertness/vigilance, orienting, and several aspects of attentional control, including switching/shifting, interference control/conflict resolution, and response inhibition.

1.2.3 Baddeley's Multicomponent Model of Working Memory

WM is a limited capacity short term memory system involved in the processing of information for current use (Waris et al., 2017). It involves the activation, maintenance, transformation, and coordination of information from short- and long-term memory and the monitoring and control of mental processes needed to carry out those actions (Baddeley, 2003; Oberauer et al., 2000). Although there are many theoretical models of WM, Baddeley (2012) multicomponent model of WM has been most prominent in educational research (Fenesi et al., 2015). The updated model to the original three–component model (Baddeley & Hitch, 1974) consists of four components of the WM system: two domain-specific short-term storage systems, one for verbal–auditory material (i.e., the phonological loop) and the other for visual and spatial material (i.e., the visuospatial sketchpad); a domain-general attentional control system (i.e., the central executive); and a passive buffer system that allows for the integration of information from WM and long-term memory and perception (i.e., the episodic buffer; Baddeley, 2010, 2012).

The phonological loop is made up of two subsystems: (1) a limited-capacity phonological store that temporarily stores verbal–auditory information, and (2) an articulatory rehearsal system that reactivates information in the phonological store through subvocalization. Without the articulatory mechanism, information in the phonological store decays rapidly (Baddeley, 2003). The type of information stored by this system includes verbal materials such as phonologically coded words and numbers, and non-auditory verbal material such as sign language material (Baddeley, 2012; Rudner & Rönnberg, 2008). Further, Baddeley (2012) proposed that non–verbal auditory information may also be stored in the phonological loop, such as music and environmental sounds.

In their review of the literature on phonological short term memory, Vallar (2006) summarized an elaborated model of the phonological loop. In the model, auditory information can directly and automatically access the phonological short-term store (i.e., the phonological store). Following phonological analysis, auditory–verbal information enters the phonological store and is retained by articulatory rehearsal. The rehearsal process directed by the articulatory rehearsal system is believed to involve cycling material between the phonological store and a phonological output buffer, a system primarily involved in articulatory programming for speech output. When verbally coded information is to be recalled, it passes through the output buffer. Neuroanatomical regions in the left hemisphere have been associated with the phonological loop's storage and rehearsal processes, with the left inferior parietal lobule associated with the phonological store, and Broca's area, the premotor area, and the supplementary motor area associated with the articulatory rehearsal process. Further, in the elaborated model of the phonological loop, visually presented verbal information (e.g., written language) enters the phonological loop through an alternative path, first being stored temporarily and analyzed as visual information, followed by a process of phonologically recoding orthographic information. The recoded information then enters the phonological output buffer wherein the information can be cycled to and from the phonological store, if required.

There is evidence for at least two subsystems of the visuospatial sketchpad (VSSP): (1) a system that holds visual information (e.g., colour, shape) and (2) a system that holds spatial information (e.g., locations and spatial relations; Baddeley, 2003, 2012; Darling et al., 2006). Baddeley (2012) also speculated that other features of objects in the environment may also be represented in the VSSP, such as tactile and kinaesthetic information. Further, just as visually presented verbal information can be recoded and maintained in the phonological loop, linguistic material can be recoded into visual mental images and maintained within the visuospatial sketchpad (Engle & Conway, 1998 for review).

The episodic buffer and central executive are the least developed components of Baddeley's (2000) multicomponent model. The episodic buffer is a limited capacity multimodal storage system wherein information from within WM, long-term memory and perception can be integrated and bound into multidimensional episodes or chunks (Baddeley, 2012; Baddeley & Hitch, 2019). Unlike the phonological loop and VSSP, its contents are assumed to be open to conscious awareness. The integration and maintenance of information within this component is reliant on the central executive component. The central executive is a domain-general limited capacity attentional control system (Baddeley, 2012). Unlike the other components, it is not a storage system. Instead, it is responsible for focusing, dividing, and shifting attention within WM, and performs executive processes to coordinate and manipulate information stored in by the other components of WM (Repovš & Baddeley, 2006).

Several paradigms have been used to study and measure WM that vary in the types of, and degree of processing demands that they place on the different components of the WM system. Some paradigms (e.g., forward span, and backward span, and the Sternberg task), hereafter referred to as WM maintenance tasks, rely primarily (solely, for forward spans) on the domain-specific storage systems of WM, depending upon the task stimuli (i.e., the phonological loop and the VSSP). Other paradigms, hereafter referred to as WM executive tasks, place greater demands on processes carried out by the central executive such as shifting between different tasks (e.g., complex span) and continuously updating the contents in WM (e.g., *n*-back and running-memory span tasks). See Appendix D for a description of WM task paradigms mentioned in this thesis. The listed tasks and upcoming reviews of research on WM in dyslexia are organized using Baddeley's (2012) multicomponent model of WM. Note that Chapters 2 and 3 includes the citations listed in the appendix.

Latent variable studies that account for measurement error and task-specific sources of variance have found strong associations between WM paradigms (Byrne et al., 2019; Schmiedek et al., 2009, 2014; Wilhelm et al., 2013). For instance, Schmiedek et al.

(2014) showed that a latent factor of two *n*-back tasks containing different stimuli (i.e., digits and spatial locations) was highly correlated with a latent factor of another WM executive paradigm, complex span (i.e., reading span, counting span, and rotation span; *r* = .69). They also found that both latent factors had high loadings onto a general WM factor, supporting the use of those paradigms as measures of the same underlying construct of WM. In another study, Byrne et al. (2019) showed that a latent factor of three *n*-back tasks containing different stimuli (i.e., numbers, letters, and spatial locations) was similarly correlated with a latent factor of three backward span tasks (i.e., digit, letter, and spatial locations; *r* = .68). The authors found, however, that a two-factor model that differentiated the backwards span and *n*-back latent factors from each other was a better fit than a single-factor model. This finding may be reflective of the distinctions between the maintenance and attentional control systems of WM; however, it could also be reflective of paradigm-specific processes. Similarly, Engle et al. (1999) showed that a latent factor of three complex span tasks (i.e., operation span, reading span, and counting span) were also highly correlated with a latent factor made of two forward and one backwards word span tasks (i.e., forward: rhyming words and non-rhyming; backwards: non-rhyming words; *r* = .68) and, like Byrne et al., they found that their two latent factors were distinguishable from one another. Although latent variable studies have provided support for the use of different WM executive paradigms to measure the same underlying construct, and the same for WM maintenance paradigms, they have also shown that WM executive and maintenance measures are distinct from one another. In this thesis, I include both verbal and visuospatial WM maintenance and WM executive measures to characterize the WM abilities of HRD students, to evaluate the relationships between WM and reading skills in HRD and NRD students, and to evaluate the effectiveness of computerized WM training in HRD students.

1.2.4 Computerized Working Memory Training

The use of computer-based WM training to improve WM functioning and related higher-order cognitive abilities has emerged as a popular area of research over the past 20 years. It has garnered substantial interest because of WM’s strong associations with important abilities and outcomes, such as fluid intelligence and academic achievement (Alloway et al., 2010; Conway et al., 2003; Engle et al., 1999; St Clair-Thompson &

Gathercole, 2006). Training often involves the intensive, repetitive practice of adaptive WM tasks, with the intended outcome of improving performance on untrained WM tasks (i.e., near transfer) and/or on measures abilities involving WM processes (i.e., far transfer). The outcomes of WM training are typically evaluated using controlled pretest–posttest designs and are measured by evaluating change in performance on outcomes of interest assessed prior to and following training. Follow-up assessments may also be carried out to evaluate whether transfer is maintained over time.

Pretest–posttest changes in performance of the training group(s) (i.e., participants who receive WM training) are typically compared to one or more control groups. There are two types of control groups: (1) passive control groups whereby participants do not receive the WM training, and (2) active control groups whereby participants practice an alternative task that does not train the construct of interest but is matched in terms of training demands. Comparison to passive control groups account for practice effects and normal changes over time; however, they do not account for other nonspecific effects such as participant expectations and regular computer use. In contrast, active control groups aim to control for those confounding factors; thus, their inclusion in cognitive training studies is considered to be best practice (Green & Bavelier, 2008; Morrison & Chein, 2011; Shipstead et al., 2012).

Gains on untrained tasks following cognitive training are believed to occur when training and transfer tasks place demands on shared cognitive processes. The capacity-efficiency model of transfer from cognitive training identified two potential mechanisms of transfer (von Bastian et al., in press; von Bastian & Oberauer, 2014). It posits that transfer from WM training occurs as the result of training-induced increases in WM capacity or WM efficiency. Training is believed to induce gains in the amount of information that can be held and processed in WM and/or to optimize WM performance within the current limits of the system. Increases in WM capacity are expected to result in broad transfer to tasks that draw on WM capacity resources. Alternatively, the efficiency of WM may be enhanced through the acquisition of knowledge and strategies, the automatization of basic processes, or, as Gathercole et al. (2019) suggested, through the acquisition and automatization of cognitive routines. Although only narrow transfer effects are expected from gains in WM efficiency from task- or material-specific strategies and knowledge, gains in WM efficiency resulting from automatization of shared underlying processes or applicable strategies or cognitive routines could lead to broader transfer (for review, see von Bastian et al., in press).

Transfer from WM training is assumed to occur as the result of anatomical or functional changes in the brain. Challenging the WM system through training is theorized to promote cognitive plasticity and to produce changes in regions of the brain responsible for WM or its underlying cognitive processes (Lövdén et al., 2010). From a neural perspective, transfer occurs when there is neural overlap between training and transfer. For example, E. Dahlin et al. (2008) conducted a neuroimaging training study whereby participants trained for five weeks on an updating task that required them to recall the last four letters of series of randomly ordered letters. They found behavioural evidence of transfer in younger adults to an *n*-back task involving updating processes but not to a Stroop task (i.e., an interference control/conflict resolution task) that did not involve updating processes. In those participants, neuroimaging revealed that the WM training task and the *n*-back task both activated the same striatal region of the brain before training and showed the same increase in activation of that region following training. In contrast, although the training task and both the *n*-back and Stroop tasks demonstrated overlap in the same frontoparietal region of the brain, the tasks did not show the same activation patterns in that region following training. E. Dahlin et al.'s findings support the notion that transfer occurs only when training and transfer tasks tap into common neural structures or networks and share the same pattern of changes in those structures or networks as a function of training.

The transfer effects of various WM training paradigms have been meta-analyzed numerous times. Most reliably, meta-analyses have found evidence for significant small to large immediate near transfer effects to untrained WM tasks (e.g., *g*s = 0.28–0.51, Melby-Lervåg et al., 2016; *d*s = 0.52–0.79, Melby-Lervåg & Hulme, 2013; *g*s = 0.55–0.63, Schwaighofer et al., 2015; *g*s = 0.18–0.59, Soveri et al., 2017). Findings regarding far transfer effects, however, have been less consistent. Some meta-analyses have found evidence of far transfer to commonly studied outcomes such as attentional control (e.g., $d = 0.32$, Melby-Lervåg & Hulme, 2013; $g = 0.16$, Soveri et al., 2017) and fluid intelligence (e.g., $g = 0.24$, Au et al., 2015; $g = 0.16$, Soveri et al., 2017); however, others have argued that there is no robust evidence for training gains beyond transfer to untrained WM tasks (Melby-Lervåg et al., 2016).

Various factors may be responsible for the observed variability in efficacy of WM training programs (for a review of potential factors impacting training effects, see von Bastian & Oberauer, 2014). Briefly, individual differences, such as initial cognitive ability, age, genetic predispositions, motivational factors, and personality traits have been associated with the extent to which individuals improve on training and transfer tasks. Moreover, the type of training paradigm used, as well as other intervention–specific factors such as the intensity and duration of the training regime and how task difficulty is adjusted, may also impact training outcomes. Inconsistencies across studies with respect to individual and training characteristics make it difficult to determine under what conditions WM is effective and for whom.

Of relevance to this thesis, the small number of WM training studies conducted in specific atypical adult learners, relative to typical learners, has made it so that meta-analyses have not been able to address whether WM training is effective in specific groups and under what conditions. The effects of WM training in specific groups, such as in those with specific LDs, may not be equivalent to the effects identified in meta-analyses with typically developing samples (e.g., Au et al., 2015; Soveri et al., 2017) or to nonspecific samples (i.e., typical and broadly defined atypical learners; Melby-Lervåg et al., 2016; Melby-Lervåg & Hulme, 2013; Schwaighofer et al., 2015). The moderating effects of learner status have been investigated in previous meta-analyses; however, authors' groupings of diverse arrays of atypical learners together (e.g., ADHD, dyslexia, LDs, low WM, and other neuropsychological disorders) limit the practical implications of their findings to specific groups of atypical learners (Melby-Lervåg et al., 2016; Melby-Lervåg & Hulme, 2013). Nevertheless, it is encouraging that broadly defined learner status has not been identified as a significant moderator of near transfer to verbal and nonverbal WM outcomes, or of far transfer to attentional control outcomes (Melby-Lervåg & Hulme, 2013) and nonverbal abilities (primarily nonverbal reasoning; Melby-Lervåg et al., 2016; Melby-Lervåg & Hulme, 2013). Thus, WM training may be useful in atypical learners; however, research with samples from specific populations of interest should be conducted before conclusions can be drawn about the effectiveness of WM training in those populations.

1.2.4.1 The N-back Task and Training. The *n*-back task is one of the most widely used WM executive paradigms in WM training studies and is used in Study 2 (i.e., Chapter 3) of this thesis. During *n*-back tasks, participants are presented with a series of auditory (e.g., words or letters) and/or visuospatial stimuli and indicate stimulus matches occurring "*n*" trials before. For instance, on an *n*-level of two, participants must indicate whether the current stimulus or stimuli matched the one(s) from two trials back. Typically, *n*-back training tasks are adaptive, with participants beginning at an *n*-level of one and progressing to higher levels based on their performance. Training studies have used both single *n*-back tasks wherein only one stimulus type is presented, and dual *n*-back tasks wherein two stimulus types presented simultaneously (Au et al., 2015; Soveri et al., 2017). *N*-back tasks involve several processes: encoding, temporary storage, and continuous updating of information in WM; inhibiting irrelevant items; and target recognition and selection (Gajewski et al., 2018; Jaeggi et al., 2008).

Au et al. (2015) conducted a meta-analysis on the effects of *n*-back WM training on fluid intelligence. They included 20 *n*-back training studies with samples of healthy adults aged 18 to 50 years and found a small, but significant transfer effect to fluid intelligence ($g = 0.24$). They also evaluated the effects of various moderators. They found that the type of control group was a significant moderator, whereby transfer effects were greater when compared to passive control groups than active control groups. Au et al. found no significant moderating effects of *n*-back type (dual or single), *n*-back stimulus type (visual or auditory), type of fluid intelligence measure administered (matrix reasoning or not; visuospatial or verbal), amount paid for participation, length of training sessions, number of training sessions, starting *n*-back level, or rate of improvement on the training task.

Following Au et al.'s review, Soveri et al. (2017) conducted a meta-analysis on the near and far transfer effects of *n*-back WM training in healthy adults aged 18 to 85 years. Thirty-three studies were included in their final analyses. Soveri et al. found moderate transfer from *n*-back training to untrained *n*-back tasks ($g = .63$), and small but significant transfer to other untrained WM tasks ($g = 0.18$) and far transfer measures of attentional control (*g* = 0.16) and fluid intelligence (*g* = 0.16). Analyses of the moderation effects of age (59 years and younger or 60 years and older), training dose (more than 6.67 hours or 6.67 hours or less), *n*-back type (dual or single), control group type (passive or active) outcome measure stimulus content (verbal or visuospatial) on transfer effects were not significant.

In summary, significant near and far transfer effects following *n*-back training in healthy adult samples have been identified, with greater near transfer than far transfer effects. Unfortunately, only one study in Au et al. and Soveri et al.'s analyses included an outcome measure of reading skill (Thompson et al., 2013; described below); thus transfer effects to reading outcomes were not evaluated. Further research evaluating the effects of *n*-back training on reading outcomes in adults is required in order to determine whether *n*-back training can be used to improve reading performance. If *n*-back training is found to be effective in improving reading performance, it could be applied as an intervention to help those with reading weaknesses or impairments. In the next section, transfer effects to reading outcomes using different kinds of WM training tasks is reviewed.

1.2.4.2 WM Training and Transfer to Reading Outcomes. Studies evaluating the transfer effects of WM training to reading outcomes have been conducted primarily in samples of typically developing children (Artuso et al., 2019; Fälth et al., 2015; Henry et al., 2014; J. S. Jones et al., 2020; Karbach et al., 2015; Loosli et al., 2012; Sánchez-Pérez et al., 2018; Söderqvist & Nutley, 2017) and in children with attention or WM deficits, and/or learning difficulties (Chacko et al., 2014; K. I. E. Dahlin, 2011; Dunning et al., 2013; Egeland et al., 2013; Gray et al., 2012; Holmes et al., 2009; Partanen et al., 2015). Most studies have trained children on WM maintenance tasks (i.e., forward and backwards spans) from the Cogmed training program (Klingberg et al., 2005). A minority have trained children on WM executive tasks such as complex span paradigms (e.g., Henry et al., 2014; Loosli et al., 2012) and *n*-back tasks (Sánchez-Pérez et al., 2018) or other tasks involving WM updating processes (Artuso et al., 2019). Transfer to measures of decoding and reading comprehension of simple sentences has generally not been observed in children following up to 18.75 hours of WM training (e.g., Chacko et al., 2014; Gray et al., 2012); however, transfer has been observed, although inconsistently, to measures of reading comprehension of passages (Artuso et al., 2019; K. I. E. Dahlin, 2011; Egeland et al., 2013; Henry et al., 2014; see Appendix E for a summary of study characteristics and training effects on reading outcomes in children).

Inconsistencies in far transfer effects to reading comprehension of passages in children may be due to the types of control groups and training paradigms used in different studies. Of the four studies in children that found significant pre-training to post-training transfer effects to reading comprehension of passages, three used a passive control group, whereby participants do not receive an intervention activity (K. I. E. Dahlin, 2011; Egeland et al., 2013; Loosli et al., 2012; Partanen et al., 2015). Although passive control groups account for practice effects and normal changes over time, they do not account for other nonspecific effects such as participant expectations and regular computer use. Thus, the significant pre-training to post-training transfer effects to reading comprehension of passages identified in the three studies with passive control groups cannot be confidently attributed to the intervention activity. Comparison to well-designed active control groups are necessary for strong conclusions regarding the efficacy of WM training to be drawn.

A review of studies in children that included an active control group suggests that challenging the attentional control system of WM may be important for transfer to reading comprehension of passages. Of the three studies in children that included an active control group, the two studies that used only three to seven hours of training on a WM executive task found evidence in favour of transfer to reading comprehension of passages (Artuso et al., 2019; Henry et al., 2014). In contrast, J. S. Jones et al. (2020) did not find evidence of transfer to reading comprehension of passages following 20 to 25 hours of training on WM maintenance tasks. Thus, the WM training literature in children provides the strongest support for transfer to reading comprehension of passages with training tasks that places high demands on the attentional control system of WM.

Only a handful of studies have evaluated transfer to reading outcomes in adults following WM training (see Appendix F for a summary of study characteristics and outcomes) and, to my knowledge, only two studies have investigated the far transfer effects of WM training to reading outcomes in young adults with cognitive and/or learning difficulties. Unfortunately, neither of those two studies included WM executive tasks as training tasks, which have been shown to have the strongest support for transfer to reading comprehension of passages in children (Artuso et al., 2019; Henry et al., 2014). Gropper et al. (2014) trained 24 undergraduate students with ADHD and/or learning disabilities for 18.75 hours on WM maintenance tasks (i.e., forward and backwards spans) from the Cogmed training program. Compared to 21 passive control participants, the authors found no evidence of transfer from training to the Nelson-Denny Reading Test – Reading Comprehension subtests (NDRT-RC). Their findings are not entirely unexpected since Cogmed training has not reliably resulted in transfer to reading comprehension of passages in children (e.g., Egeland et al., 2013; J. S. Jones et al., 2020; Partanen et al., 2015).

In another study, Shiran and Breznitz (2011) trained native Hebrew speaking university students for a total of six hours on a battery of backward span and verbal, auditory, and visuo-spatial short-term memory tasks from the CogniFit Personal Coach training program. Participants that scored below a specified cut-off on a normative diagnostic test for adult reading disabilities were categorized as impaired readers. All other participants were categorized as skilled readers and scored above a specified cut-off on word and pseudoword decoding subtests. They were assigned to either the training task (*n*=26 impaired readers; *n*=35 skilled readers) or to an active control group that completed a self-paced sentence reading and comprehension task (*n*=15 impaired readers; *n*=15 skilled readers). For participants in the training groups, the authors found a significant main effect of time whereby both impaired and skilled readers improved from pre-training to post-training on measures of decoding, reading rate, and reading comprehension. Reader status and time did not interact. The authors did not provide enough information about their reading comprehension measure to be classified as either sentence or passage comprehension. No effects of time were observed in either of the control groups suggesting no or limited normally occurring changes over time, practice effects, and nonspecific training effects that could have contributed to significant improvements in reading observed in the training groups. Critically, however, the authors did not directly compare the training groups to the active control groups, thus limiting the extent to which conclusions can be drawn about the effectiveness of the training program. Despite their lack of direct comparison to an active control group, Shiran and Breznitz's findings provide initial support for WM training as a means of improving reading performance in skilled and impaired university student readers.

Studies have also evaluated transfer to reading outcomes in adults following training on WM executive tasks, but only in young to middle-aged adult samples not selected for reading difficulties. In a study by Chein and Morrison (2010), a sample of 20 native English speaking university students, unselected for reading ability, trained for a total of 10 to 15 total hours on adaptive verbal and visuospatial complex span tasks. The number of to-be-recalled items on the recall task of both complex span training tasks (i.e., recall letters or spatial locations) increased or decreased based on participants' performance on both the recall task and the secondary processing task (i.e., lexical decisions or symmetry judgements). Compared to a passive control group of 22 participants, the authors found significant training effects for the intervention group on a measure of cognitive control and on the NDRT-RC. Chein and Morrison also found that gains in reading comprehension performance were significantly positively correlated with gains on the visuospatial training task and not the verbal training task. The authors argued that the visuospatial training task was likely more successful than the verbal training task at engaging the domain-general central executive component of WM because verbal rehearsal strategies are highly practiced and automatic. When a process can be carried out successfully without or with little conscious processing, it utilizes few, if any, attentional resources (Moors & De Houwer, 2006). Thus, Chein and Morrison concluded that enhancing the attentional control component of WM may be the mechanism by which WM training enhances reading comprehension. Although Chein and Morrison's findings provide initial support for the potential for WM training to aid reading performance in adults, it remains possible that their observed transfer effects could be due to nonspecific artifacts of the training task (e.g., expectation effects) not controlled for by the passive control group.

In contrast to Chein and Morrison's findings, others have failed to find evidence of transfer to the NDRT-RC following training on WM executive training tasks compared to active controls. In one study, Redick et al. (2020) trained a sample of adults between 18 to 30 years of age ($M = {\sim}20.5$) for five hours on one of two adaptive verbal complex span tasks. Both training tasks were operation span tasks; in one (i.e., operation-letters; n

= 30), the recall task consisted of only letters, and in the other (i.e., operation-mix; *n* = 27), the recall task alternated between having to remember letters, numbers, and words. The performance of WM training groups on outcome measures pre- and post-training were compared to an active control group (*n* = 29) that trained on an adaptive visual search task. The number of to-be-recalled items on the WM training tasks and the number of distractors on the active control task increased and decreased during training sessions based on participants' performance on their assigned task. Redick et al. found no evidence of transfer from either WM training group to the NDRT-RC compared to the active control group.

Although the conflict between Redick et al.'s findings and those of Chein and Morrison may have been due to Redick et al.'s use of an active control group that accounted non-specific effects of the WM training, other study characteristics could have also impacted the effectiveness of their WM training program. For instance, participants in Redick et al.'s study received five to 10 fewer hours of training than the participants in Chein and Morrison's study; this lower dose might not have been sufficient for transfer to occur (Pappa et al., 2020; Schwaighofer et al., 2015; but see Au et al., 2015; Melby-Lervåg & Hulme, 2013). Moreover, unlike Chein and Morrison, Redick et al. did not include a visuospatial complex WM training task. This is notable given that Chein and Morrison found that in their sample, gains in reading comprehension of passages were associated with gains on their visuospatial training task and not on their verbal training task. Participants in Redick et al.'s study might have relied on verbal rehearsal strategies to complete their assigned training task, resulting in insufficient demands being placed on the domain-general attentional control system of WM.

In another study, Thompson et al. (2013) also failed to find evidence of transfer to the NDRT-RC following training on a WM executive training task compared to active controls. The authors trained a sample of adults between 18 to 45 years of age (*M* = 21.2) for approximately eight hours on an adaptive dual *n*-back task. Like Chein and Morrison, Thompson et al.'s training programs included both verbal and visuospatial stimuli, but the stimuli were presented simultaneously and the dose of training was lower. The performance of the WM training group (*n* = 20) on outcome measures pre- and post-training was compared to a passive control group (*n* = 19) and an active control group (*n*

= 19). The active control condition consisted of an adaptive multiple object tracking (MOT) task wherein participants were required to track four dots amongst 12 distractor dots as they moved on a computer screen. The *n*-level on the dual *n*-back task and the speed at which the dots moved in the MOT task increased and decreased during training sessions based on participants' performance on their assigned task. Thompson et al. found no evidence of transfer to the NDRT-RC for the WM training group compared to the active and passive control groups; however, participant baseline performance was likely close to ceiling on the NDRT-RC, with a mean grade-level equivalence was at approximately 17.1 reflecting 87% to 90% correct responses. Failure to observe significant transfer effects on the NDRT-RC following WM training might have been the consequence of insufficient test sensitivity at higher levels of reading comprehension ability. Alternatively, WM training may simply be less effective for individuals with high baseline skills and may be more beneficial for those with baseline deficits or weaknesses who have more room to improve (Au et al., 2015; Holmes et al., 2009; Jaeggi et al., 2008; Klingberg et al., 2005).

In summary, there is evidence, although not consistent evidence, that WM training can lead to gains on tasks evaluating reading comprehension of passages. The strongest support for transfer to reading comprehension of passages comes from studies with children and adults using training tasks that place high demands on the attentional control system of WM (Artuso et al., 2019; Chein & Morrison, 2010; K. I. E. Dahlin, 2011; Egeland et al., 2013; Henry et al., 2014). Although one study in adults evaluated and found evidence for transfer of WM training to decoding outcomes (Shiran & Breznitz, 2011), research findings across multiple studies in children have found little evidence for transfer to measures of decoding. A meta-analysis by Melby-Lervåg et al. (2016) offered support for far transfer from WM training to reading comprehension (g = 0.12 to 0.15) but not to decoding (g = 0.01 to 0.08) in people in children to young adulthood. The inclusion of visuospatial stimuli or both verbal and visuospatial stimuli in the training program may be important for transfer to reading comprehension measures (e.g., Chein & Morrison, 2010). Unfortunately, differences between training studies, such as in participants' baseline skills, training tasks, outcome measures, and types of control groups impact the interpretation of study findings and make it difficult to compare across studies (Pergher et al., 2020). Moreover, limited comparability across studies interferes with researchers' abilities to draw strong conclusions regarding what is necessary for transfer to occur and for whom. Nevertheless, some studies in children with attention deficits and learning difficulties (K. I. E. Dahlin, 2011; Egeland et al., 2013) and in typically developing children and adults (Artuso et al., 2019; Chein & Morrison, 2010; Henry et al., 2014; Loosli et al., 2012; Shiran & Breznitz, 2011; Söderqvist & Nutley, 2017) provide initial support for the potential for WM training to aid reading comprehension. Further research with active control groups and in specific populations of interest, such as HRD university students, is needed to determine whether and what kind of WM training can be used to improve important outcomes for certain people (e.g., reading performance in HRD students).

Chapter 2: Study 1 – Attention, working memory, and reading in undergraduate students with and without a history of reading difficulties

2.1 Introduction

Understanding the mechanisms underlying students' reading difficulties is important given the importance of reading to academic achievement (Gottfried et al., 2015; Reder, 1999; Snow & Strucker, 1999). There is empirical evidence demonstrating that aspects of attention and working memory (WM), two multifaceted higher-level cognitive functions, are related to reading performance (Follmer, 2018; Larsen et al., 2022; Ober et al., 2020; Peng et al., 2018; Swanson & Jerman, 2007). The goal of the current study was to further establish the link between adult reading performance and both attention and WM. Specifically, we aimed to determine whether weaknesses in attention and WM may be contributing to previously identified weaknesses in the decoding and reading comprehension skills of university students with a history of reading difficulties (HRD) and may be potential targets for supporting those students.

2.1.1 Defining Attention and WM

Attention is both a form of alertness as well as a mechanism of resource allocation (Raz & Buhle, 2006), selectively prioritizing sensory information for the purpose of directing focus to the most important stimuli (Carrasco, 2011). According to Posner and colleagues' model of attention, distinct but interacting brain networks are responsible for attentional functions including *vigilance/alerting* to achieve and maintain a mental state of readiness, *orienting* to and selecting target stimuli or locations for optimal processing, and *executive control* of attention (here after referred to as attentional control) for the deployment, coordination, and regulation of our limited attentional resources (Fernandez-Duque & Posner, 2001). Attentional functions develop throughout childhood (Best & Miller, 2010; Pozuelos et al., 2014) with vigilance and attentional control continuing to develop in adolescence (Best & Miller, 2010; Crone et al., 2018; Morandini et al., 2020; Waszak et al., 2010).

WM is a limited capacity multicomponent short-term memory system involved in the processing of information in support of a current goal/task (Waris et al., 2017). It is not entirely distinct from attention as it involves attentional control processes. According to Baddeley's multicomponent model of WM, it consists of a domain-general attentional control system (i.e., the central executive); two domain-specific short-term storage systems, one for verbal-auditory material (i.e., the phonological loop) and the other for visual material (i.e., the visuospatial sketchpad); and a passive buffer system that allows for the integration of information from WM and long-term memory and perception (i.e., the episodic buffer; Baddeley, 2010, 2012). WM development is prolonged, occurring throughout childhood and adolescence (e.g., Luna et al., 2004; Zhang et al., 2020).

2.1.2 HRD Students and Evidence Suggesting that Their Attention and WM May be Affected

HRD university students have been identified as being at potential academic risk (Bergey et al., 2017; Chevalier et al., 2017). These students, who self-identify as having early reading difficulties by means of their responses to a questionnaire (i.e., the Adult Reading History Questionnaire – Revised; Parrila et al., 2003), have been found to have reading difficulties that persist into adulthood. On average, they have levels of decoding and timed passage reading comprehension skills that are similar to their peers with recent diagnoses of learning disabilities and as much as four to five grade levels below their peers without histories of reading difficulties (NRD; Deacon et al., 2012; MacKay et al., 2019). Decoding is defined as the ability to read written words and non-words with accuracy and/or fluency. HRD university students have also demonstrated, on average, lower levels of untimed passage reading comprehension performance than their diagnosed peers (Deacon et al., 2012; see Appendix B for summary of research findings on HRD students' reading skills). Further, HRD students have relative weaknesses in several underlying language and literacy-specific processes compared to their NRD peers (i.e., phonological awareness, phonological memory, morphological awareness, and orthographic processing; Al Dahhan et al., 2014; Deacon et al., 2012; Metsala et al., 2019; Parrila et al., 2007). Although HRD students are able to cope with academic demands to the extent that they gain admission to higher education, there is evidence that they encounter academic challenges in the university setting. Studies show that they earn lower first-year grade point averages (GPA; Bergey et al., 2017; Chevalier et al., 2017) and successfully complete fewer course credit than their NRD peers (Bergey et al., 2017).

HRD university students' responses on self-report measures suggest that they experience challenges with focused attention and the use of cognitive strategies. Bergey et al. (2017) administered the Learning and Studying Strategies Inventory (LASSI) to HRD and NRD university students. The authors found that HRD students self-reported having more difficulty maintaining their attention on academic tasks (Concentration subscale) and less effective use of cognitive-related strategies and skills for learning (Information Processing subscale) than their NRD peers. Bergey et al. also found that NRD students' ratings of their abilities to direct and maintain their attention on academic tasks was positively related to their GPA, whereby greater reported attention abilities were associated with higher GPAs. In contrast, no relationships between self-reported attention on academic tasks and GPA was identified in their HRD sample. The authors argued that the self-report nature of the LASSI may not have captured the full extent of HRD respondent's behaviours and difficulties. Most studies on the relationship between self-estimates and performance-based measurement of cognitive abilities have found only weak to moderate correlations suggesting that people may not be good estimators of their cognitive abilities (Freund & Kasten, 2012; Salthouse & Siedlecki, 2005; Volz-Sidiropoulou & Gauggel, 2012). Thus, although Bergey et al.'s (2017) findings signal the possibility that HRD students experience more challenges than their NRD peers in attention and related cognitive functions, objective measurement is necessary for the accurate characterization of this population's cognitive abilities and the optimal identification of targets for supports.

Although there has been no published research that has objectively measured the attention and WM abilities of HRD undergraduate students, we can look to studies with other samples with reading difficulties, such as those diagnosed with dyslexia, to help us generate hypotheses about their cognitive strengths and weaknesses. Dyslexia is a neurobiological and developmental learning disability primarily characterized by difficulties in reading and spelling (Roitsch & Watson, 2019). Current research on dyslexia has found that it is best considered as a condition that exists on a continuum of cognitive (Swanson et al., 2006) and reading difficulty severities (Ellis, 2016; e.g., Crisp & Lambon Ralph, 2006; Dandache et al., 2014). This raises the possibility that HRD undergraduate students represent a milder or higher functioning form of dyslexia (Deacon et al., 2012) and have many of the same cognitive challenges identified in the dyslexia literature. As attention and WM functions develop throughout childhood and in some cases into adolescence (e.g., Best & Miller, 2010; Siegel, 1994) and the cognitive processes and strategies that children and adults rely on to read differs (e.g., Greenberg et al., 2002), we focus our review of the literature primarily on studies with adult samples. We review studies with adolescents only in cases where research in adults is not available or is extremely limited.

2.1.2.1 Attention in Adults With Dyslexia. Compared to their non-dyslexic peers, adults with dyslexia have been found to show deficits on some attentional functions but not others. The performance of adults with dyslexia has been found to be the same as their non-dyslexic peers on simple reaction time (SRT) tasks (Iles et al., 2000; Nicolson & Fawcett, 2000; Rüsseler et al., 2006) and continuous performance tasks (Alloway et al., 2014). Those tasks measure one's ability to maintain a mental state of readiness to quickly detect and respond to relevant stimuli (from here on referred to as vigilance processing speed). In contrast, those with dyslexia have been found to demonstrate lower performance that their non-dyslexic peers on measures of vigilance that require discrimination judgments and choices (from here on referred to as vigilance decision speed). For example, Nicolson and Fawcett (2000) found that adolescents with dyslexia ($M_{\text{age}} = 15$) performed just as well as age-matched controls on two SRT tasks but had significantly longer initial response latencies for finger responses on their choice reaction time (CRT) task (i.e., a combination of both SRT tasks) and longer and less accurate final CRT response latencies in both finger and foot responses. Similarly, with respect to orienting of attention, adults with dyslexia have demonstrated poorer performance than their non-dyslexic peers on common measures of orienting, including spatially cued target detection tasks (Buchholz & Davies, 2008; Goldfarb & Shaul, 2013) and visual search tasks (Buchholz & McKone, 2004; Iles et al., 2000; M. W. Jones et al., 2008).

With respect to the attentional control, findings have varied depending on the control process evaluated. In terms of switching/shifting attention, comparing adults with dyslexia to those without, Stoet et al. (2007) found no evidence of greater costs of switching between colour discrimination and shape discrimination tasks for those with dyslexia. In contrast, Smith-Spark et al. (2016) found that adults with dyslexia showed significantly greater switch costs than their non-dyslexic peers when alternating between adding and subtracting numbers. In terms of response inhibition (i.e., inhibition of dominant, automatic, or especially powerful responses to stimuli in the environment), adults with dyslexia have demonstrated deficits in contrast to their non-dyslexic peers on Go/No-go and Stop-Signal tasks. Smith-Spark et al. found that adults with dyslexia were significantly less accurate than their non-dyslexic peers on a visual Go/No-go (80% Go) task and Goranova (2019) found that university students with dyslexia had significantly longer stop signal reaction times on a Stop-Signal task with visual go stimuli and auditory stop-signal.

Previous studies have also found evidence of interference control/conflict resolution deficits in adults and adolescents with dyslexia on Stroop, Simon, and Flanker tasks. Adults (Proulx & Elmasry, 2015) and adolescents (i.e., age 15 years; Kapoula et al., 2010) with dyslexia have shown greater interference effects than their non-dyslexic peers on Stroop tasks. Further, on an auditory stimulus Simon task, Gabay et al. (2020) found that Simon effect costs for reaction time and error rate (incongruent trials > congruent trials) were significantly greater for adults with dyslexia than those without. On visual stimulus Simon tasks, however, neither Gabay et al. nor Goranova found group differences in Simon effect costs. Gabay et al. suggested that the differences in their findings on their visual and auditory stimulus Simon task could be reflective of a specific vulnerability that adults with dyslexia have towards conflicting/distracting auditory information. In contrast to Gabay et al. and Goranova’s findings on visual Simon tasks, several researchers have found group differences on Flanker tasks that are inherently visual in nature. Goldfarb and Shaul (2013) and Goranova (2019) found that interference effects for reaction time (incongruent trials > congruent trials) on a horizontal Flanker task were significantly greater for adults with dyslexia than those without. Similarly, Mahé et al. (2014) found differences in interference effects between adults with and without dyslexia on a vertical flanker task; although the authors found no group differences for reaction time, they found significant interference effects for error rates limited to those with dyslexia. Differences in interference effects on Flanker tasks and Simon tasks with visual stimuli in adults with dyslexia may be reflective of differences in the processes involved in interference control/conflict resolution on the two tasks (Mansfield et al., 2013).

In summary, adults with dyslexia have demonstrated challenges, compared to their non-dyslexic peers, in attention in the areas of vigilance decision speed, attentional orienting, response inhibition, and interference control/conflict resolution (most consistently on Flanker and Stroop tasks). Evidence for switching/shifting attention deficits in dyslexia has not been consistently demonstrated but remains a possibility. HRD undergraduate students, who may represent a milder or higher functioning form of dyslexia, may have similar attentional weaknesses as those found in adults diagnosed with dyslexia.

2.1.2.2 Working memory in Adults With Dyslexia. WM impairments are one of the most frequently identified cognitive characteristics of dyslexia (e.g., Ghani & Gathercole, 2013; Smith-Spark & Fisk, 2007; Vasic et al., 2008). WM has typically been measured in the reading literature using WM maintenance tasks that rely primarily on the domain-specific WM storage systems of WM, and WM executive tasks that place greater demands on the attentional control component of WM (i.e., the central executive as seen in Baddeley's (2012) multicomponent model of WM). Previous research has found that adults with dyslexia show consistent WM deficits in comparison to their non-dyslexic peer, with the majority of studies finding that adults with dyslexia perform significantly worse than their non-dyslexic counterparts on both verbal measures of WM maintenance and on WM executive tasks (e.g., Ghani & Gathercole, 2013; Horowitz-Kraus & Breznitz, 2009; Smith-Spark et al., 2016; Smith-Spark & Fisk, 2007). Adults who were diagnosed with dyslexia in childhood have also demonstrated lower performance than age-matched skilled readers on verbal WM executive measures (Ransby & Swanson, 2003). Although research using visuospatial WM tasks is more limited, a handful of studies have found that adults with dyslexia also perform worse than adults without dyslexia on visuospatial WM executive measures (Ghani & Gathercole, 2013; Smith-Spark et al., 2003, 2016; Smith-Spark & Fisk, 2007); however, to a lesser extent than on verbal WM measures (Smith-Spark et al., 2016; Smith-Spark & Fisk, 2007). Furthermore, Smith-Spark et al. (2003) found that adults with dyslexia perform worse than their non-dyslexic peers on visuospatial WM only when WM updating demands are high (i.e., greater demands placed on the central executive system of WM). Overall, these findings suggest that adults with dyslexia have weaknesses in WM primarily associated with the verbal storage and domain-general attentional control components of WM. These WM challenges may also be experienced by HRD students.

2.1.3 Relationships of Reading with Attention and WM

Evidence from longitudinal studies support the importance of WM and attention for reading achievement. In unselected samples of children, researchers have found that early (i.e., preschool and kindergarten) attention behaviours, visuospatial orienting ability, and WM skills are associated with reading skills during early elementary school years (i.e., first to fourth grades; Franceschini et al., 2012; Larsen et al., 2022; Morgan et al., 2019; Stipek & Valentino, 2015). WM has also been found to predict reading growth in older children and adolescents. For example, Swanson and Jerman (2007) conducted a longitudinal study with 11- to 17-year-old children and adolescents across three waves of assessment spaced one year apart. The authors found that WM was significantly associated with growth in passage reading comprehension and decoding skills in participants with IQ scores greater than 90 that were classified as either skilled readers (i.e., above the 45th percentile on a word reading test) or as having reading difficulties (i.e., below 25th percentile on a word reading test). Moreover, the authors found that processes of the central executive component of WM (i.e., controlled attention), rather than the phonological loop, best predicted growth in reading. Further, WM has been found to predict the development of second language reading in adult learners. For instance, Sagarra (2017) found that WM predicted second language reading development in 18- to 30-year-old native-English speakers. The author found that performance on a WM measure with taxing processing demands (i.e., demanding of the central executive component of WM), but not on a WM measure with low processing demands, predicted Spanish reading performance over the duration of one semester of a university level Spanish course. Sagarra and Swanson and Jerman's findings indicate that attentional control processes may be especially important for reading proficiency.

Cross-sectional studies also suggest that attentional control and WM are involved in reading. Relationships between reading skills and attentional control and WM functions identified in early childhood appear to remain in adulthood. In a meta-analytic review of 65 studies with non-clinical samples of children and adolescents (range 4.42–17 years old), Ober et al. (2020) identified significant positive associations between decoding skills and switching/shifting, interference control/conflict resolution, and WM (including both WM maintenance and WM executive measures; average *r* = .28–.34). The authors found that effect size estimates for those relationships did not change with age for interference control/conflict resolution or WM, but that effect size estimates decreased with age for switching/shifting. In another meta-analysis of 29 studies in participants from ages 6 years to young and middle adulthood, Follmer (2018) found significant correlations between reading comprehension and switching/shifting (*r* = .39), response inhibition/interference control/conflict resolution (*r* = .28) and WM (*r* = .38). The authors found that the relationship between reading comprehension and WM and attentional control/executive functioning (i.e., switching/shifting, response inhibition/interference control/conflict resolution, planning, sustained attention, and monitoring) overall did not vary significantly with age; however, the magnitude of the relation was greater for children and adolescents (*r* = .33–.38) than for adults (*r* = .25). The findings of both meta-analyses indicate that the magnitude of the relationships between reading skills and attentional control and WM functions may change with age but that the relationships remain universal across age, at least into young to middle adulthood.

Although relationships between reading and attentional control and WM functions remain in adulthood, the exact nature of the relationships may shift as individuals learn to read and their attentional and WM functions develop. Findings from a meta-analysis by Peng et al. (2018) offers support to this idea. In their review of 197 studies with non-clinical and typically developing individuals, Peng et al. found that, after controlling for publication type, grade level, bilingual status, and domain of WM (i.e., verbal or non-verbal), WM was significantly correlated with decoding (*r* = .28) and reading comprehension (*r* = .31). Consistent with Ober et al. and Follmer's meta-analytical findings, Peng et al. found that the relationships between WM and reading comprehension were stronger before grade four than in later grades, and that the relationship between WM and decoding did not differ across grades. The authors also found that prior to the 4th grade, verbal WM and visuospatial WM reading predicted reading equally; however, at/after the 4th grade, verbal WM was more strongly associated with reading performance than visuospatial WM. This change in the relationships between WM and reading from younger to older readers is important as it suggests that the pattern of those relationships may vary as a function of age or as a function of reading and/or WM development and skill.

Given the potential impact of age, reading expertise, and cognitive ability on the relationships between reading and cognitive functions, hypotheses about those relationships in populations with atypical reading and/or cognitive profiles should be generated based on previous research in those specific populations. When such research is unavailable or limited, hypotheses may be drawn from similar populations. To date, the relationships between reading skills and attention and WM functions have not been previously investigated in HRD university students; thus, a review of studies with typical and atypical learners in similar reading and cognitive developmental stages as HRD students is pertinent. Unfortunately, to our knowledge, no meta-analyses on this topic have focused on late adolescent and/or adult populations, nor on reading disabled samples. For this reason, we summarize the findings of individual studies with adolescent/adult samples with varying reading abilities next.

Individual studies with adolescents and adults have identified positive associations between reading and aspects of WM and attentional control. For instance, Arrington et al. (2014) used path analysis to investigate the contributions of sustained attention, response inhibition, cognitive inhibition (i.e., suppression of task-irrelevant or inappropriate information), and verbal WM maintenance to reading in a large sample of adolescents (aged 11 to 17-year-olds) with a range of reading abilities (44% with poor reading abilities). The authors found significant direct effects of response inhibition and WM on decoding. They also found significant direct effects of sustained attention and WM on reading comprehension. Furthermore, WM was indirectly predictive of reading comprehension, through decoding. In another study with a large sample of older children and adolescents (i.e., 8–16 years old) with school histories of reading disability and/or ADHD (56.8%) and without, Christopher et al. (2012) used a latent variable structural equation modelling approach to investigate the role of cognitive functions in predicting decoding and combined language and reading comprehension. The authors found that the relationships between response inhibition and both decoding and comprehension were significant when response inhibition was entered as the sole cognitive predictor in the model; however, after controlling for other cognitive constructs (i.e., processing speed, naming speed, and WM or response inhibition), WM but not response inhibition was independently related to both outcomes. Lastly, studies with young adult samples have found significant relationships between performance on verbal WM executive measures and reading comprehension (e.g., De Beni et al., 2007; Hannon, 2012). In summary, previous work in adolescents and adults have found consistent evidence for a positive relationship between verbal WM and decoding and reading comprehension performance. Previous studies have also found associations between response inhibition and decoding; however, response inhibition may not be a unique predictor of decoding beyond the variance in decoding attributed to general cognitive ability.

Some studies have also found significant relationships between reading comprehension and latent or composite factors of attentional control and WM in adults. In one such study, Follmer and Sperling (2019) found that in adults aged 18 to 71 (mean = 36.98 years), a single latent factor made up of measure of switching/shifting and WM measures, as well as verbal fluency measures, contributed to reading comprehension directly and that the relationship was mediated by vocabulary ability. Similarly, Cartwright et al. (2020) looked at how a composite component consisting of measures of switching/shifting, interference control/conflict resolution, and WM functions contributed to reading comprehension in general sample of university students (mean age = 20.48 years, *SD* = 2.79 years). Their composite component was indirectly associated with reading comprehension through relationships with word reading skills, language comprehension, and reading-specific cognitive flexibility. There was no direct association between their composite component and reading comprehension. Overall, these findings provide support for ongoing positive relationships between reading comprehension and attentional control and WM.

2.1.4 Summary and Rationale

In summary, HRD undergraduate students have been identified as an academically vulnerable group of students (Bergey et al., 2017; Chevalier et al., 2017) that present with many of the same challenges in reading as their peers with documented learning disabilities or dyslexia (Deacon et al., 2012). Difficulties in higher-order cognitive skills, such as attention and WM, may be in part responsible for HRD students' reading challenges. Previous research has found that, relative to adults without dyslexia, adults with dyslexia have weaknesses in vigilance decision speed, attentional orienting, response inhibition, interference control/conflict resolution, and WM (e.g., M. W. Jones et al., 2008; Mahé et al., 2014; Nicolson & Fawcett, 2000; Smith-Spark et al., 2003, 2016). There is some, although inconsistent evidence, that adults with dyslexia may also have relative weaknesses in switching/shifting attention (Smith-Spark et al., 2016; cf. Stoet et al., 2007). Moreover, findings from longitudinal and cross-sectional studies supports the involvement of attention and WM processes in reading growth and performance (e.g., Arrington et al., 2014; Follmer, 2018; Hannon, 2012; Larsen et al., 2022; Swanson & Jerman, 2007). The pattern of the relationships between reading and attentional control and WM processes may change as reading and cognitive skills develop (Peng et al., 2018).

Unfortunately, there are gaps in the literature that limit our understanding of the contributions that attention and WM processes make to reading performance and impairment in adults. To our knowledge, there has been no published work in adults on the relations of vigilance and orienting attention with reading performance, for either decoding or reading comprehension. Very few studies and reviews have examined the relationships between those reading skills and switching/shifting, response inhibition, interference control/conflict resolution, and WM in adults. Further, although attentional control functions are contended to be separate yet interrelated and interdependent (Miyake et al., 2000), meta-analytic reviews frequently group measures of different attentional control functions into one factor. This limits our understanding of if and how each function uniquely contributes to reading performance. Moreover, there is an absence of research on the moderating effects of learner status (e.g., learning disabled or typical learners) on the relationships between reading skills and attention and WM functions.

These gaps in the literature are important because they reflect an incomplete understanding of the attention mechanisms underlying reading in adulthood and the important factors related to attention that could contribute to reading impairment in adulthood. There are several roles that attention and WM processes may have in reading performance. For instance, readers must remain focused on the reading task at hand and on aspects of the text or mental representations of the text to achieve their reading goals. Presumably, they must also be able to orient their visuospatial attention along letters of the text for decoding (Vidyasagar & Pammer, 2010), and along lines of text for sentence and passage comprehension. Moreover, for effective decoding, readers are likely to engage WM and attentional control processes. For instance, blending phonemes into words might involve the storage and processing of phonological sequences in WM. For reading comprehension, WM and attentional control could be critical for maintaining and updating relevant information from the text, integrating that information with knowledge in long term memory, and inhibiting the activation of irrelevant information (for reviews see Butterfuss & Kendeou, 2017; Dehn, 2008). Given the multitude of ways that attention and WM functions may be involved in reading performance, understanding which aspects of attention and WM that are important for adult reading could have implications for our understanding of adult reading problems. Further, such an understanding could help to identify targets for intervention with potentially widespread effects.

2.1.5 Study 1

In the current study, we aimed to determine whether problems with attention and WM may be contributing to HRD students' weaknesses in reading. No research, to date, has objectively evaluated HRD students' attention and WM abilities, nor evaluated the relationships between reading and those cognitive abilities in HRD students. Study 1 had two objectives: 1) to characterize the attention and WM abilities of HRD undergraduate students; and 2) to evaluate the relationships between reading and both attention and WM in adults, specifically in HRD and NRD university students.

To accomplish our first objective, we compared the reading, attention, WM abilities of HRD undergraduate students to the performance of NRD undergraduate students. We predicted that, in line with Deacon et al. (2012) and Metsala et al. (2019)'s previous work, HRD students would show lower levels of decoding, reading rate, and reading comprehension performance compared to the NRD group. We also predicted that HRD students would self-report having more difficulty maintaining their attention on academic tasks than their NRD peers as reported by Bergey et al. (2017). Although no prior research has objectively investigated the attention and WM abilities of HRD students, we hypothesized that they might present with weaknesses, relative to their NRD peers, in attention and WM previously found to be low in adults with dyslexia. Those hypothesized weaknesses include vigilance decision speed, orienting, aspects of attentional control (i.e., response inhibition and interference control/conflict resolution), WM maintenance in the verbal domain, and WM executive processes.

For our second study objective, we sought to further explore the relationships between attention, WM, and both decoding and reading comprehension in HRD and NRD university students. When examining the associations between cognitive functions and reading comprehension, we controlled for decoding ability as it is a known predictor of reading comprehension performance (García & Cain, 2014; Tighe & Schatschneider, 2016). We were interested in how the relationships might vary by reading history. Due to the insufficient power of our sample to detect what are typically very small interaction effects of categorical moderators in multiple regression (Aguinis et al., 2005), we examined the relationships in HRD and NRD students, separately, to identify possible group differences.

Given that distinct brain networks have been identified as responsible for different attentional functions and that those networks have been found to be independent and interactive (Petersen & Posner, 2012), we sought to determine how attention functions related to reading skills both independently and in combination with one another. To explore the relationships between attention and reading for the first time in HRD and NRD university students, we examined the extent to which different functions of attention (i.e., vigilance, orienting, and attentional control) were uniquely and collectively related to decoding and reading comprehension performance. Based on previous findings in adolescent samples (e.g., Christopher et al., 2012; Ober et al., 2020), we predicted that poorer inhibitory control may be associated with poorer decoding performance. We did not generate specific a priori hypotheses regarding all other relationships due to the scarcity or absence of research on those relationships in adult and/or adolescent samples.

To investigate the relationships between WM and reading, we examined the extent to which verbal and visuospatial measures uniquely related to the reading performance. To preserve power and to limit the influence of shared variance amongst maintenance and control measures of WM, we examined the relationships between reading performance and WM maintenance and WM executive performance in separate models. We predicted that better WM performance, primarily in the verbal domain (Peng et al., 2018), would be positively associated with better decoding and reading comprehension performance.

2.2 Method

2.2.1 Participants.

A total of 103 undergraduate students between the ages of 17 and 24 years old, attending a large Canadian university, enrolled to participate in this research: 51 with a history of reading difficulties (HRD) and 52 with no history of reading difficulties (NRD; see Table 2.1 for a summary of sample demographics). History of reading difficulties was determined for each participant based on their proportion score on the elementary school subscale of the Adult Reading History Questionnaire-Revised (ARHQ-R; see Appendix A). Using cut-off scores implemented in previous studies (e.g., Bergey et al., 2017; Deacon et al., 2012), individuals with scores between 0 and .25 were classified as NRD and those with scores of .37 and above were classified as HRD. Students with scores between .25 and .37 were excluded from the study. Consistent with previous research, HRD students that self-reported an earlier diagnosis of a learning disability were not excluded from the study (e.g., Deacon et al., 2012; diagnostic information is described in the next paragraph). Participants were recruited through three avenues: e-mail invitation from a database of previous research participants; an undergraduate research participant pool; and on-campus poster advertisement. Participants received an honorarium and/or course credit for their participation.

All participants self-reported English as their first language (spoken, reading and writing), normal or corrected to normal vision, no history of head injury with loss of consciousness for more than five minutes, no current diagnosis of a severe neurological or psychiatric disorder, and no commencement or change in dose of a psychotropic medication within four weeks of beginning the study. As part of the study, participants completed a brief background and screening questionnaire used to confirm participant eligibility and to characterize the sample. The questionnaire included questions about demographic information, academic history, and relevant health information (see Appendix G**)**. Of those who enrolled in this study, 51 NRD and 51 HRD met the eligibility criteria and participated in the study. One participant in the NRD group and four participants in the HRD group reported receiving an earlier diagnosis of attention deficit hyperactivity disorder (i.e., ADHD), one participant in the HRD group reported receiving earlier diagnoses of both ADHD and a learning disability, and four participants in the HRD group reported receiving an earlier diagnosis of a learning disability. Of those who reported an earlier diagnosis of a learning disorder (i.e., 9.8% of the HRD sample), only one specified that it was a diagnosis of dyslexia. There were no differences between groups with regards to age and years of education, and anti-depressant/anti-anxiety medication usage; however, there were more female NRD participants and more HRD participants used stimulant medications than NRD participants (see Table 2.1 for a summary of group differences).

2.2.2 Measures

2.2.2.1 Reading. Decoding was measured using the Single Word Efficiency and Phonemic Decoding Efficiency subtests from the Test of Reading Efficiency (TOWRE). Reading comprehension and reading rate were measured using the Nelson-Denny Reading Test – Reading Comprehension subtest (NDRT-RC; see Table 2.2 for a description of each task and the variables used from each measure for the analyses).

2.2.2.1.1 The Test of Reading Efficiency (TOWRE). The TOWRE is a measure of decoding; it measures a reader's efficiency and fluency of word reading, sight word recognition, and phonemic decoding (Torgesen et al., 1999). Participants were administered the Single Word Efficiency (TOWRE SWE) subtest and the Phonemic Decoding Efficiency (TOWRE PDE) subtest. Form A and Form B of the TOWRE were used in this study. The TOWRE (Torgesen et al., 1999) has been shown to have strong internal consistency (using alternate-form reliability for both subtests and total scores; $\alpha = .93–.96$), two-week test–retest reliability ($r = .82–.97$), and inter-rater reliability ($r = .99$ across subtests and total score). It has also been demonstrated to have alternate form equivalence ($r = .86$ or higher for different age intervals) and to have high relationships between its subtests ($r = .77–.96$). Torgesen et al. (1999) also found that the TOWRE has good concurrent validity with other measures of word attack skills and sight word reading ($r = .86–.94$). To address our second research question regarding the relations between reading skills and cognitive functions, a composite score (i.e., Decoding Composite) used to measure decoding ability was computed by summing the TOWRE SWE and TOWRE PDE raw total scores together.

2.2.2.1.2 The Nelson-Denny Reading Test – Reading Comprehension (NDRT-RC). The NDRT-RC (Brown et al., 1993) is a measure of reading comprehension and reading rate. Form G and Form H of the NDRT-RC were used in this study. It was selected as a measure for this investigation because it is a common measure of adult reading performance, including adults with a history of reading difficulties (Deacon et al., 2012; McGonnell et al., 2007; Parrila et al., 2007). It has been found to have high internal consistency ($\alpha = .92$; Georgiou & Das, 2016) and adequate alternate-form reliability ($r = .81$; Brown et al., 1993). It has also been found to be positively correlated with verbal portions of aptitude tests (e.g., $r = .71$ with the College Board Scholastic Aptitude Test and $r = .71$ with the American College Testing Program; Wood, 1982).

2.2.2.2 Self-Reported Attention on Academic Tasks.

2.2.2.2.1 The Learning and Studying Strategies Inventory (LASSI): Concentration Subscale. The LASSI Concentration Subscale (LASSI-Conc) is a self-report measure of attention as it relates to academic tasks (see Table 2.3 for a description of the measure and the variable used for analyses). The LASSI-Conc has been shown to have strong internal consistency ($\alpha = .84$) and test–retest reliability ($r = .85$; Weinstein, 2002). Overall, the LASSI has been shown to be able to differentiate academically successful university students from unsuccessful ones (Marrs et al., 2009). Furthermore, individual LASSI scales and latent factors within the measure have been found to be good predictors of academic performance (Cano, 2006; Marrs et al., 2009; Seabi, 2011; West & Sadoski, 2011).

2.2.2.3 Attention and Working Memory (WM). See Table 2.3 for a detailed description of the measures listed below and the variables used from each for the analyses.

2.2.2.3.1 The Dalhousie Computerized Attention Battery (DalCAB)-Modified Version. The DalCAB contains 8 subtests of attention and working memory. It was designed to measure Posner and colleagues' systems of attention (i.e., vigilance/alerting, orienting, and executive control (i.e., attentional control; Fan et al., 2002, 2005; Fernandez-Duque & Posner, 2001; Petersen & Posner, 2012)). Performance on the DalCAB has been shown to have good test-retest reliability ($r = .71$–$.87$) and all tasks in the battery have been shown to replicate well established response patterns and effects in the cognitive psychology literature (S. A. H. Jones et al., 2016). Furthermore, S. A. H. Jones et al. (2015) conducted an exploratory factor analysis of task performance on the DalCAB and found a 9-factor model. This model provided evidence for the battery as a comprehensive measure of attention, in general, and as a measure of vigilance/alerting, orienting, and attentional control, more specifically.

2.2.2.3.2 Operation Span Task. The Operation Span (Engle, Kane, et al., 1999; modified from Kane et al., 2004) is a computerized verbal measure of WM executive processes (Kane & Engle, 2003). Two different forms of the Operation Span (i.e., different lists of stimuli) were used in this study. It has been shown to have strong internal consistency (α = .84–.86; Engle, Tuholski, et al., 1999; Kane et al., 2004; Redick et al., 2012; Unsworth et al., 2005) and test–retest reliability (*r* = .83; Redick et al., 2012; Unsworth et al., 2005). It has also been shown to converge with other WM executive measures (*r* = .55–.73; Kane et al., 2004; Redick et al., 2012).

2.2.2.3.3 Symmetry Span Task. The Symmetry Span is a computerized visuospatial measure of WM executive processes (Kane et al., 2004). It has been shown to have strong internal consistency (α = .76–.81; (Engle, Tuholski, et al., 1999; Kane et al., 2004; Redick et al., 2012) and test–retest reliability (*α* = .77; (Redick et al., 2012; Unsworth et al., 2009). It has also been shown to converge with other WM executive measures (*r* = .55–.71; Kane et al., 2004; Redick et al., 2012).

2.2.3 Procedures

Participants came into the Cognitive Health and Recovery Lab testing space in the Life Sciences Centre at Dalhousie University to complete informed consent, screening, and measures of reading, attention, and WM. Following informed consent, participants completed a self-report screening and background questionnaire (see Appendix G) to gather relevant demographic, academic, and health information, and to confirm eligibility for study participation.

Participants were then administered, in a set order, measures of reading, self-reported attention on academic tasks, attention, and WM (see Appendix H for the test list order). Since there were two forms of the TOWRE, NDRT-RC, and Operation Span, two test lists (i.e., Test List A and B) with the different forms were created and counterbalanced across groups. Approximately half of the NRD (*n* = 25) and HRD (*n* =

26) participants were assigned to Test List A. Two test lists were required as some participants continued to a training study in Study 2 (see details below) and these data were used as baseline measures. The approach to random test list assignment was slightly different between the NRD and HRD groups because of a need to balance HRD characteristics within recruitment blocks. After completion of the study, participants were debriefed and provided with either course credits or financial compensation.

Computerized outcome measures, including the short version of the Dalhousie Computerized Attention Battery (DalCAB), the Operation Span, and the Symmetry Span, were performed on an iMac®, 27-inch, 2.7 GHz Intel Core i5. Participants were centered 19.75 inches from the screen. Responses were made with a two-button mouse (for the DalCAB), a computer keyboard (for the Operation Span and Symmetry Span tasks), as well as paper and pencil (for the Symmetry Span). Computer screen brightness was set to 50% and volume was set to the maximum volume. To limit computer screen glare during computerized test administration, a dim lamp was placed behind and to the left of the participant, out of sight, and the overhead lights were turned off.

2.3 Results

2.3.1 Data Cleaning

The data for each measure for each group (i.e., HRD and NRD), were screened for extreme outliers using a cut-off of four standard deviations from the group mean. The data for one NRD participant was removed from the DalCAB Simple RT Reaction Time (RT) variable, and the data for another NRD participant was removed from the DalCAB Choice RT variable. The data for the latter participant was also excluded from the Dual Task Cost RT variable as Choice RT Reaction time is used in the calculation of that variable. No other extreme outliers were identified. The means and standard deviations for each measure, following the removal of outliers, are presented in Table 2.4 for each group.

2.3.2 Research Question 1: What are the Reading, Attention, and WM Abilities of Individuals With a History of Reading Difficulties (HRD) Compared to Those Without (NRD)?

Our first research aim was to characterize the reading, attention, and WM abilities of HRD undergraduate students; this was done in contrast to their NRD peers. First, measure variables (except for the LASSI-Conc) were grouped into factors to contrast HRD and NRD students' performances at level of attention network, WM process across stimulus domains, and reading skills. Variables from the DalCAB were grouped into two factors of vigilance (i.e., vigilance processing speed and vigilance decision speed), one orienting factor, three factors of attentional control (i.e., switching/shifting, interference control/conflict resolution, and response inhibition), and a factor of WM maintenance. Included variables from the DalCAB were selected from the most reliable single measures (S. A. H. Jones et al., 2016) and factor groupings were determined based on conceptual relationships between variables (see Petersen & Posner, 2012) and their loadings in S. A. H. Jones et al. (2015)'s factor analysis (see Table 2.5). The Operation Span and Symmetry Span tasks, two measures of WM executive processes found to be highly correlated in the literature (e.g., Foster et al., 2015; Kane et al., 2004), were grouped into a WM executive factor. The variables from the TOWRE and NDRT-RC were grouped into a Reading factor.

To compare the performance of the HRD group to the NRD group at the factor level, we conducted Welch's t-tests (Delacre et al., 2017) for each test variable (see Table 2.4 for a summary of the results) and calculated Cohen's *d* for each t-test as an effect size estimate of the group differences. The 95% confidence interval of Cohen's *d* (i.e., 95% $CI = d \pm 1.96\sqrt{V_d}$) was computed after deriving the variance of Cohen's *d* using the following formula (Borenstein et al., 2009).

$$V_d = \frac{n_1 + n_2}{n_1 n_2} + \frac{d^2}{n_1 + n_2}$$

For each factor, a meta-analysis random effects model (Borenstein et al., 2009) was used to calculate an overall Cohen's *d* with 95% confidence intervals using the Cohen's *d* values and 95% confidence intervals from the Welch's t-tests. Cohen's *d* values were interpreted as representative of small ($d = 0.20$), medium ($d = 0.50$), and large ($d = 0.80$) based on guidelines proposed by Cohen (1969). Effects sizes with 95% confidence intervals for each variable and weighted random factor were plotted on forest plots (see Figure 2-1 to Figure 2-9 for forest plots and Table 2.4 for variable-level effect sizes). Significant effects are indicated by confidence intervals that do not cross zero.

Differences at the variable level are described for factor groupings with significant effects.

2.3.2.1 Reading. The HRD group's performance on the reading factor was significantly lower than NRD group (*d* = 0.69, 95% CI [0.46, 0.92]; Figure 2-1). The groups differed significantly on all individual reading variables, except for NDRT-RC reading rate (Table 2.4). Compared to the NRD group, the HRD group read fewer single words correctly on the TOWRE-SWE, Welch's *t*(99.7) = 2.83, *p* < .01, *d* = 0.56, 95% CI [0.17, 0.96], and fewer non-words on the TOWRE-PDE, Welch's *t*(89.0) = 4.28, *p* < .001, *d* = 0.85, 95% CI [0.44, 1.25]. The HRD group got a smaller percentage of reading comprehension questions correct on the NDRT-RC than the NRD group, Welch's *t*(88.4) = 4.20, *p* < .001, *d* = 0.94, 95% CI [0.53, 1.35].

2.3.2.2 Self-reported Attention on Academic Tasks. On the LASSI, the HRD group self-reported significantly poorer ability to direct and maintain attention on academic tasks than NRD participants, Welch's *t*(82.2) = 4.1, *p* < .001, *d* = 0.84, 95% CI [0.42, 1.26].

2.3.2.3 Attention. In terms of vigilance, there were no group differences on the vigilance: processing speed factor (*d* = -0.15, 95% CI [-0.43, 0.13]; Figure 2-2). In contrast, HRD group showed significantly lower performance than the NRD group on the vigilance: decision speed factor (*d* = 0.44, 95% CI [0.16, 0.72]; Figure 2-3) with longer reactions times on the Choice RT task, Welch's *t*(86.4) = 2.19, *p* < .05, *d* = 0.43, 95% CI [0.04, 0.83]), and on the feature search visual search task (Feature Search RT), Welch's *t*(94.2) = 2.25, *p* < .05, *d* = 0.42, 95% CI [0.05, 0.84] (Table 2.4).

HRD group showed significantly lower performance than the NRD group on the orienting factor (*d* = 0.37, 95% CI [0.09, 0.65]; Figure 2-4) with longer reactions times on the conjunction search visual search task (Conjunction Search), Welch's *t*(92.8) = 2.10, *p* < .05, *d* = 0.42, 95% CI [0.02, 0.81] (Table 2.4).

In terms of Attentional Control, there were no group differences on factors of switching/shifting (*d* = 0.06, 95% CI [-.47, .58]) or interference control/conflict resolution (*d* = 0.04, 95% CI [-0.36, 0.44]; Figure 2-5 and Figure 2-6, respectively). In contrast, HRD participants showed significantly lower performance than the NRD participants on the response inhibition factor (*d* = 0.37, 95% CI [0.09, 0.64]) with the

HRD group showing more false alarms than the NRD group on the rare target item Go/No-go task (GNG 20% Go), Welch's $t(85.7) = 2.11$, $p < .05$, $d = 0.42$, 95% CI [0.03, 0.81] (Table 2.4; Figure 2-7).

2.3.2.4 Working Memory. There were no group differences on the WM maintenance factor ($d = 0.26$, 95% CI [-0.01,0.54]; Figure 2-8). In contrast, compared to the NRD group, the HRD group showed significantly lower performance on the WM executive factor ($d = 0.67$, 95% CI [0.19, 1.15]; Figure 2-9) with lower total scores on the Operation Span, Welch's $t(94.2) = 4.62$, $p < .001$, $d = 0.91$, 95% CI [0.05, 1.32], and on the Symmetry Span, Welch's $t(99.8) = 2.17$, $p < .05$, $d = 0.43$, 95% CI [0.04, 0.82] (Table 2.4).

2.3.3 Research Question 2: Do Attention and WM Predict Decoding and Reading Comprehension?

The second research question that we aimed to address was whether attention and WM are related to reading performance in HRD and NRD students. To accomplish this, multiple regression analyses with listwise deletion for missing data were conducted with reading outcome as the dependent variable (i.e., either the Decoding Composite or percent of correct answers on the NDRT-RC). Due to the insufficient power of our sample to detect what are typically very small interaction effects of categorical moderators in multiple regression (Aguinis et al., 2005), we examined the relationships in HRD and NRD students, separately, to identify possible group differences. As a follow-up check of these analyses, we conducted additional multiple regression analyses across all participants (i.e., HRD and NRD) with group as a predictor. Group by predictor interactions were included in the final step of these models only for predictors that were found to be significant in either of the separate HRD and NRD group regression models. Detailed results of these follow-up analyses are presented in Appendix I and Appendix J and are summarized below. We interpreted the results with caution due to sample size. To confirm that it was appropriate in our HRD and NRD samples to combine the number of correctly pronounced items on the TOWRE SWE and TOWRE PDE together to form a Decoding composite, bivariate correlations were conducted between the two measures. Reassuringly, the two subtests were highly correlated with one another ($r_{49} = .69$ in both groups).

To investigate the relationship between attention and reading, composite means for each attention network, for both the HRD and NRD groups, were first created by averaging the z-scores of the DalCAB variables within each network (see Table 2.5 for a list of the network groupings). A total of six composite scores were created to represent the attention networks: (1) vigilance: processing speed, (2) vigilance: decision speed, (3) orienting, (4) attentional control: switching/shifting, (5) attentional control: interference control/conflict resolution, and (6) attentional control: response inhibition. A regression analysis was conducted with all six attention composites entered together into the model as predictors with the Decoding Composite or Reading Comprehension as outcome variables. Doing so allowed for the evaluation of the extent to which the distinct but interacting networks of attention (Petersen & Posner, 2012) were uniquely and collectively related to decoding and reading comprehension performance. Age and years of education were not significantly correlated with the reading outcomes and therefore, they were not included in the model (See Appendix P and Appendix Q for bivariate correlations between participant characteristics, attention and WM predictors, and reading outcomes across and within the HRD and NRD participant groups). To investigate the relationship between WM and reading, the measures of WM maintenance (i.e., Item Memory and Location Memory tasks on the DalCAB) were included as predictors within one regression analysis and the WM executive measures (i.e., the Operation Span and the Symmetry Span) were included in another regression analysis. For models with reading comprehension as the outcome, the Decoding Composite was entered as the first step of the model, followed by the attention composites or WM measures. We controlled for decoding ability as it is a known predictor of reading comprehension performance (García & Cain, 2014; Tighe & Schatschneider, 2016)

2.3.3.1 Decoding. The results of the regression analyses with the Decoding Composite as the dependent variable are presented in Table 2.6.

2.3.3.1.1 NRD. The linear combination of attention measures was significantly related to performance on the Decoding Composite and accounted for 26% of the variance. Only the Vigilance: Decision Speed Composite was a significant and unique negative predictor related to decoding ($\beta = -.58$). The linear combination of the WM maintenance measures was significantly related to performance on the Decoding

Composite and accounted for 13% of the variance. Only Item Memory error performance was a significant and unique negative predictor related to decoding (*β* = -.43). The linear combination of the WM executive measures was significantly related to decoding and accounted for 28% of the variance. Only Operation Span Total was a significant unique predictor related to decoding (*β = .54).*

2.3.3.1.2 HRD. The linear combination of attention measures was not significantly related to performance on the Decoding Composite and only accounted for 14% of the variance. None of the attention measures were uniquely related to the composite. The linear combination of the WM maintenance measures was significantly related to performance on the Decoding Composite and accounted for 16% of the variance. Only Location Memory error was a significant and unique negative predictor of decoding (*β = -.32)*. The linear combination of the WM executive measures was significantly related to the Decoding Composite and accounted for 15% of the variance. Only Operation Span Total was a significant and positive unique predictor related to the Decoding Composite (*β = .32).*

2.3.3.1.3 Follow-Up Check for Group Differences. Multiple regression analyses with group by predictor interaction terms revealed a significant group by Location Memory error interaction (*β = -.23*), confirming between group differences in the relationship between Location Memory error and decoding. Better accuracy on the Location Memory task was associated with better decoding performance only in the HRD group. The follow-up analyses did not find significant group by Vigilance: Decision Speed Composite or group by Item Memory %Error interactions. Instead, Vigilance: Decision Speed Composite and Item Memory %Error were significant unique predictors of the Decoding Composite across HRD and NRD students (*β = -.35* and *β = -.26*, respectively), suggesting more consistency in those relationships between the groups than suggested by the analyses conducted separately for the HRD and NRD groups. For further details of the follow-up analyses, see Appendix I.

2.3.3.2 Reading Comprehension. The results of the regression analyses with NDRT-RC %Correct as the dependent variable are presented in Table 2.7.

2.3.3.2.1 NRD. In step 1 of each model, the Decoding Composite was not significant and accounted for only 7% of the variance in reading comprehension. The linear combination of attention measures was not a significant predictor related to reading comprehension, accounting for an additional 7% of the variance. The linear combination of WM maintenance measures was also not significantly related to reading comprehension and only accounted for an additional 2% of the variance. The linear combination of the WM executive measures was significantly related to reading comprehension and accounted for an additional 20% of the variance. Only Operation Span Total was a significant and positive predictor related to reading comprehension (β = .46).

2.3.3.2.2 HRD. The Decoding Composite predicted a significant portion of the variance in reading comprehension, accounting for 13% of the variance in Step 1 of the regression models. The linear combination of attention measures was not a significant predictor related to reading comprehension, accounting for an additional 4% of the variance. The linear combination of WM maintenance measures was significantly related to reading comprehension and accounted for an additional 14% of the variance. Only Location Memory error was a significant predictor related to reading comprehension (β = -*.43)*. The linear combination of the WM executive measures was significantly related to reading comprehension and accounted for an additional 16% of the variance. Only Operation Span Total was a significant and positive predictor related to reading comprehension (β = .48).

2.3.3.2.3 Follow-Up Check for Group Differences. Multiple regression analyses with group by predictor interaction terms revealed a trend (i.e., p = .09) group by Location Memory %Error interaction (β = -*.15*) in support of between group differences in the relationship between Location Memory %Error and reading comprehension. Better accuracy on the Location Memory task was associated with better reading performance only in the HRD group. For further details of the follow-up analyses, see Appendix J.

2.4 Discussion

Study 1 aimed to identify areas of cognitive challenge for university students with a history of reading difficulties (HRD) and their associations with their reading performance. To do this, we first sought to characterize the reading skills, attention, and WM abilities of HRD university students by comparing them to their peers without a history of reading difficulties (NRD) on measures of those functions. We then explored the relationships between reading performance and attention and WM in both HRD and NRD students. Overall, the results of this study further our understanding of HRD university students and give new insights into how their relative cognitive strengths and weaknesses may contribute to their reading performance. We discuss the results of the study in detail and their implications next.

2.4.1 Characterizing Undergraduate Students With a History of Reading Difficulties

2.4.1.1 Reading. In our sample, HRD students showed lower reading performance, overall, compared to NRD students; the size of the overall effect was medium. The magnitude of the group differences on individual reading measures were medium for one measure of decoding (i.e., TOWRE word reading efficiency), and large for another measure of decoding (i.e., phonemic decoding efficiency) and a measure of untimed reading comprehension. These findings are consistent with previous investigations of HRD university student reading abilities defined by the same criteria used in this study (Deacon et al., 2012; Metsala et al., 2019).

Although our sample of HRD students demonstrated lower decoding and reading comprehension performance than the NRD students, they did not demonstrate a slower reading rate than the NRD group as did the HRD participants in Deacon et al. (2012)'s study; rather, there was no difference in reading rate between the groups. Failure to find group differences in reading rate may reflect the heterogeneity in HRD students' approaches to reading and their reading abilities (Deacon et al., 2012). A large portion of HRD participants in our study (i.e., 73%) and Deacon et al.'s (i.e., 48%) might have prioritized reading speed over reading comprehension; they demonstrated lower untimed reading comprehension than their NRD peers (i.e., at least one standard deviation (*SD*) below the NRD mean) and preserved reading rate (i.e., within one SD of, or greater than one SD than the NRD mean). An additional 16% of HRD participants in Deacon et al.'s study, and none in our study, demonstrated preserved untimed reading comprehension and slower reading rates than the NRD group. This pattern may reflect the prioritization of comprehension over reading rate. As suggested by Walczyk et al. (2007), readers may adjust their reading rate as a compensatory mechanism for difficulties in reading comprehension. Moreover, another portion of HRD participants in our study (i.e., 27%) and Deacon et al.'s study (i.e., 29%) showed both lower performance on untimed reading comprehension and slower reading than the NRD group rates (i.e., one *SD* below the NRD mean), suggestive of concurrent weaknesses in reading comprehension and reading rate or perhaps weaknesses in reading comprehension that could not be entirely compensated for by reading rate adjustment. Given the heterogeneity of reading performance and behaviours within Deacon et al.'s and our samples, further investigation is warranted to explore whether and to what extent this heterogeneity reflects differences in reading strategies (Chevalier et al., 2017), differences in reading performance along a continuum, and/or are within-group subgroups with distinctive reading and cognitive profiles (O'Brien et al., 2012).

2.4.1.2 Self-Reported Attention on Academic Tasks. Consistent with Bergey et al. (2017)'s findings, HRD students in our study reported having a great deal more difficulty maintaining their attention on academic tasks than their NRD peers. In our sample, this effect was large (i.e., $d = 0.84$), whereas Bergey et al. (2017) found a small effect (i.e., $d = 0.35$). This difference in effect size may have been due to differences in sample participant characteristics and a product of self-selection bias in our sample. Bergey et al. (2017) sample consisted, exclusively, of students entering their first year at a large Canadian university, whereas participants in our study included students at all stages of their undergraduate degrees, with only 37% in their first year of study. Furthermore, for our study, HRD students were invited to participate in both the current study as well as a follow-up attention and WM training study. Thus, in contrast to Bergey et al. (2017)'s sample, the HRD participants in our study had more exposure to the high demands of university education and may have been more likely to have subjective attentional concerns which were reflected in their responses on the LASSI. These findings further highlight the heterogeneity of the HRD population. They also indicate that self-report measures of cognitive functions may be easily influenced by environmental factors and thus, comparison on such measures across studies must be done with caution.

2.4.1.3 Attention. In this study, we defined attention using Petersen and Posner (2012)'s model of attention. The model describes attention as involving distinct but interacting brain networks that are responsible for three attentional functions: vigilance, orienting, and executive control of attention (i.e., referred to as attentional control throughout this document). We compared HRD students to their NRD peers on individual tasks and factors of vigilance, orienting, and three aspects of attentional control (i.e., switching/shifting, response inhibition, and interference control/conflict resolution).

On objective measures, compared to their NRD peers, HRD students showed lower performance with small effect sizes on factors of orienting and response inhibition, using variables from a visual search task and Go/No-Go task, respectively. These findings are consistent with those found in adults with dyslexia on other visual search measures of orienting (Buchholz & McKone, 2004; Iles et al., 2000; M. W. Jones et al., 2008) and on measures of response inhibition (Goranova, 2019; Smith-Spark et al., 2016). HRD students also showed lower performance than NRD students, with small effects, on a factor of vigilance decision speed using variables from a choice RT and a visual search task, but not on a factor of vigilance processing speed using variables from a simple reaction time task. Consistent with previous findings in adolescents and adults with dyslexia, HRD students demonstrated an intact ability to maintain a mental state of readiness to quickly detect and respond to relevant stimuli (Alloway et al., 2014; Nicolson & Fawcett, 2000; Rüsseler et al., 2006; Taroyan et al., 2007), but inefficiencies in processing with the added complexity of making discrimination judgments and choices.

There were no group differences in performance on the switching/shifting factor. This finding was consistent with Stoet et al. (2007)'s but not Smith-Spark et al. (2016)'s findings on task switching paradigms in university students with dyslexia in comparison to university students without dyslexia. As Smith-Spark et al. (2016) argued, however, differences in findings across studies on switching/shifting performance of adults with dyslexia may not represent contradictory findings but rather reflect methodological differences. Dual-task paradigms, like the one used in the current study, require the coordination of attentional resources in WM between two tasks simultaneously, whereas task-switching paradigms require sequential switching of attention between tasks and inhibition of previous task sets (Koch et al., 2018; Strobach et al., 2018). Performance on these different paradigms, therefore, involve switching/shifting attention in coordination with different underlying cognitive mechanisms. Thus, it may not be appropriate or informative to compare the performance of HRD students on a dual-task paradigm to previous findings in adults with dyslexia on task-switching paradigms. Future research may benefit from using both dual-task and task switching paradigms to achieve a more thorough measurement of switching/shifting abilities in adults with dyslexia and HRD students.

Whereas no group differences between HRD and NRD students were found on the flanker task used to measure interference control/conflict resolution ability in the present study, differences on flanker task performance between adults with and without dyslexia have been reported previously. Mahé et al. (2014) found significant interference effects for error rates on a vertical flanker task limited to those with dyslexia but no group differences for reaction time, and Goldfarb and Shaul (2013) found greater interference effects for reaction time (incongruent trials > congruent trials) on a horizontal flanker task in adults with dyslexia than those without. Failure to find group differences in interference control/conflict resolution in our sample of HRD and NRD students, when such deficits have been observed in adults with dyslexia (e.g., Mahé et al., 2014), may reflect a true difference in the cognitive profiles of HRD students and adults diagnosed with dyslexia.

Alternatively, failure to find group differences in interference control/conflict resolution using the DalCAB's flanker task could be due to differences in the tasks used. Goldfarb and Shaul (2013), Goranova (2019), and Mahé et al. (2014)'s task stimuli consisted of arrows whereas ours used same coloured shapes. This is notable as arrows have been shown to be powerful stimuli with exogenous characteristics, triggering automatic attentional shifts (Spagna et al., 2014; Tipples, 2002, 2008); therefore, Goldfarb and Shaul, Goranova, and Mahé et al.'s behavioural findings could be explained, at least in part, by difficulties with orienting attention (Buchholz & McKone, 2004; Iles et al., 2000; M. W. Jones et al., 2008) and not necessarily or solely by difficulties with interference control/conflict resolution. Furthermore, Mahé et al.'s flanker task was more challenging than ours. The authors presented their target and flankers either to the left or right of a central fixation cross and participants made a response by pressing a key on the right side of the keyboard (with their right hand) or the left side of the keyboard (with their left hand). Thus, interference control/conflict resolution demands were not limited to the flankers, as was the case with our task.

Instead, response conflict was also present when the correct key response was on the opposite side of the keyboard as the location of the target and flankers. It may be that that HRD students do experience more difficulty with interference control/conflict resolution than their NRD peers, but only when task demands are high. Future research should consider investigating whether HRD students' performance on measures of interference control/conflict resolution fluctuates with changes in processing demands.

2.4.1.4 Working Memory. In this study, we defined WM using Baddeley's multicomponent model (Baddeley, 2012; Fenesi et al., 2015), and included measures of WM maintenance that rely primarily on the domain-specific WM storage systems of his model (i.e., the phonological loop and visuospatial sketchpad), and WM executive tasks that place greater demands on the attentional control system of WM (i.e., the central executive). As we expected, there were group differences between HRD and NRD students on measures of WM; however, these differences were limited to WM executive tasks. The HRD students in our sample did not perform significantly different from their NRD peers on both the verbal and visuospatial Sternberg tasks used to measure WM maintenance. This is in contrast to previous studies that have demonstrated WM impairments in undergraduate students with dyslexia, compared to non-dyslexic controls, on similar verbal Sternberg tasks (e.g., Horowitz-Kraus & Breznitz, 2009). However, the HRD group did show poorer performance than the NRD group on WM executive tasks, with larger effects on the verbal measure (i.e., Operation Span; $d = 0.92$) than the visuospatial measure (i.e., Symmetry Span; $d = 0.43$). These findings mirrored Smith-Spark et al. (2016)'s findings that university students diagnosed with dyslexia performed worse than their peers without dyslexia on the same WM executive tasks, with larger effects on the Operation Span task ($\eta^2_p = .13$) than the Symmetry span task ($\eta^2_p = .09$). Our findings indicate that although HRD students have some challenges in WM deficiencies consistent with those observed previously in adults diagnosed with dyslexia, they may not be as extensive. It is possible that one reason why many HRD university students can cope with academic demands prior to post-secondary education, without receiving a diagnosis of a learning disability and accompanying supports, is that they are able to effectively utilize their preserved WM storage resources to compensate for weaknesses in reading and other cognitive functions. To better characterize HRD undergraduate students' cognitive profiles in relation to their diagnosed peers, and to explore differences in their approaches to academic tasks, further research directly comparing the two groups is required.

Our findings provide support for the hypothesis that HRD students may represent the same underlying population as their diagnosed peers (Deacon et al., 2012) but have less extensive cognitive impairments. Unlike adults with dyslexia who have demonstrated weaknesses on WM executive measures and verbal WM maintenance measures (e.g., Horowitz-Kraus & Breznitz, 2009; Smith-Spark et al., 2016), HRD students' performances on verbal WM maintenance measures appear to be preserved. Furthermore, the identification of lower performance of HRD students than their NRD peers on both verbal and visuo-spatial WM executive measures, with larger effects in the verbal domain, provides support for both modality-specific (i.e., verbal) and modality-general impairment of WM in this reading-impaired populations (Carretti et al., 2009; Smith-Spark et al., 2003). Before strong conclusions may be drawn regarding similarities amongst HRD students and adults diagnosed with dyslexia, however, direct group comparisons are needed between the two groups.

2.4.2 Relationships of Reading with Attention and WM.

2.4.2.1 Attention. Attention was not significantly related to reading comprehension in either group. Different patterns of relationships between attention and decoding performance were identified in the HRD and NRD groups. No components of attention were significant predictors of decoding in the HRD group. In the NRD group, however, the vigilance decision speed composite was uniquely related to decoding, with faster vigilance decision speed associated with better performance on time-limited decoding tasks. These findings indicate that successful and efficient decoding ability in NRD university students may be dependent, at least in part, on a greater ability to remain vigilant/on-task and to quickly make decisions (i.e., how to pronounce the words and pseudowords in the case of the decoding task). Failure to observe an association between vigilance decision speed and decoding in the HRD group might have been due to their overall deficiency in vigilance decision speed resources, as indicated by lower performance than NRD students on the vigilance decision speed factor. HRD students might not have the resources necessary and available for accurate and efficient decoding.

In terms of attentional control, we did not observe any relationships between response inhibition and decoding in either group, which was contrary to previous findings using a similar Go/No-Go response inhibition task in adolescents with a range of reading abilities (Arrington et al., 2014). A possible explanation for this difference in our findings is more limited variability in reading abilities within our samples compared to Arrington et al.'s (2014) sample. In their study, Arrington et al. (2014) included adolescents with a range of reading abilities, and oversampled for students with poor reading ability (i.e., 44% of their sample), whereas we analyzed our reading groups separately. To compare more closely to Arrington et al.'s (2014) work, we reanalyzed the relationships between attention and reading across groups and found that response inhibition, measured by the percentage of false alarms made on a Go/No-Go task, was in fact a significant related to decoding ($\beta = -.21, p < .05$). These results offer further support for the involvement of response inhibition in decoding, and to our knowledge, are the first to demonstrate this relationship in an adult sample. When reading words and non-words, response inhibition may be involved in inhibiting the activation of competing grapheme-phoneme correspondences or orthographically similar words (Seidenberg, 2005; Seidenberg & McClelland, 1989). Moreover, for words that do not follow regular letter-to-sound rules (e.g., yacht, pint, both), response inhibition may be involved in inhibiting grapheme-phoneme conversion to reduce competition with retrieved whole-word pronunciations (Cummine et al., 2018).

2.4.2.2 Working Memory. Consistent with previous findings, WM performance was significantly related to both HRD and NRD reading performance (Arrington et al., 2014; Christopher et al., 2012; Hannon, 2012); however, the patterns of the relationships were different for the two groups. Beginning with the findings in the NRD group, decoding and reading comprehension performance were best predicted by verbal WM tasks, with the verbal WM maintenance and WM executive tasks predicting decoding, and only the verbal WM executive task predicting reading comprehension after entering decoding into the model. This finding is consistent with previous work suggesting that in later reading development, the relationship between WM and reading is primarily in, or perhaps limited to, the verbal-domain (Carretti et al., 2009; Peng et al., 2018). Furthermore, only WM executive and not WM maintenance tasks significantly predicted

NRD reading comprehension performance, highlighting the involvement and importance of central executive processing in reading comprehension (Arrington et al., 2014). This finding is consistent with previous research showing that measures that tax both the storage and processing components of WM are better predictors of reading comprehension than measures with temporary storage requirements in the absence of processing requirements (i.e., short-term memory tasks; Daneman & Merikle, 1996).

In contrast to the pattern of findings in the NRD group, decoding and reading comprehension performance was not limited to associations with the verbal WM domain in the HRD group. Better performance for both reading outcomes was associated with better performance on the visuospatial WM maintenance and verbal WM executive tasks. The involvement of WM in the visuospatial domain in predicting HRD reading, rather than solely in the verbal domain, may reflect the underdevelopment of their lower-level reading abilities and verbal knowledge. As demonstrated in Peng et al. (2018)'s meta-analysis, during early stages of reading development in childhood (i.e., before grade 4), performance on measures of verbal and visuospatial WM predict reading performance equally, but that as children are believed to build stronger foundations in lexical representations and verbal knowledge (i.e., after grade 4), greater demands are placed on the verbal-specific processes in WM. When lower-level reading processing skills are underdeveloped, as in undergraduate HRD students (Deacon et al., 2012; Metsala et al., 2019), WM ability in any domain may be required or utilized to aid reading performance.

HRD students could be consciously or unconsciously engaging in a compensatory strategy to aid in decoding and reading comprehension. Specifically, they may use visual memory resources to compensate for weaknesses in verbal skills. Studies by Bacon and colleagues (Bacon et al., 2013; Bacon & Handley, 2010, 2014) have suggested that adults with dyslexia rely on visuospatial memory to assist with reasoning, a skill predictive of reading comprehension development (Peng et al., 2019; Swart et al., 2017) and performance (LaRusso et al., 2016; Ribeiro et al., 2016). Bacon and colleagues have speculated that adults with dyslexia may have a tendency to convert written information into visualized images to help maintain the information in mind, while adults without dyslexia employ verbal strategies (Bacon & Handley, 2010, 2014). Although the implementation of a visuospatial memory compensatory strategy is a compelling explanation for the different patterns observed between WM and reading in HRD and NRD groups, it is important to note that visuospatial memory has not been researched in HRD students. Further research is necessary to understand the visuospatial memory processes of those students and other reading-impaired populations, and to explore their roles in reading performance.

2.4.3 Theoretical Implications

The findings of this study have theoretical implications. Specifically, the results offer insight into which aspects of WM may be most important for reading proficiency and performance. Swanson and Jerman (2007) described two models for how WM may underly reading growth: one model that argued that inefficiencies in the phonological loop component of WM constrain growth in literacy and another model that argued that the attentional control functions of the WM central executive system constrain growth in literacy. To test the two models, Swanson and Jerman conducted a three-wave longitudinal study of 11- to 17-year-old skilled and unskilled readers. In support of their second model, the authors found that processes of the central executive component of WM, rather than the phonological loop, best predicted growth in reading. Although our results cannot speak to how WM influences the growth in reading skills, they can speak to what component(s) of WM may be most important for reading proficiency and problems. First, we found that the HRD group presented with weaknesses in reading performance and on WM executive tasks, that rely heavily on attentional control processes, but not on the WM maintenance tasks. If the storage components of WM (i.e., the phonological loop and/or the visuospatial sketchpad) were crucial for reading, we would have expected to find reading history group differences on one or both WM maintenance tasks. Further, we found that only a WM executive task, and no WM maintenance tasks, was reliably associated with reading performance across HRD and NRD students. Thus, our findings offer support for Swanson and Jerman's second proposed model highlighting the importance of the central executive component of WM in reading, and, more broadly, for the inclusion of WM in theoretical models of reading. Moreover, the group differences reported here provide converging evidence for Swanson and Jerman's longitudinal findings.

Based on our results, Swanson and Jerman's second model may be expanded to include other cognitive predictors of reading. Although we found differences between HRD and NRD students on basic attention measures (i.e., measures of vigilance decisions speed and orienting of attention), those measures were not reliable predictors of reading performance. We did, however, find that HRD students presented with weaknesses in response inhibition and that response inhibition predicted decoding across our entire sample of HRD and NRD students. Based on the results from this study and of others (e.g., Arrington et al., 2014; Cartwright et al., 2020; but see Christopher et al., 2012), we suggest that a modified version of Swanson and Jerman's model pertaining to current reading performance could include specific controlled attention processes acting independently of the WM central executive.

2.4.4 Limitations and Future Directions

Some limitations of the present study are important to mention and may be addressed in future research. First, we considered the potential similarities and differences between HRD undergraduate students and those diagnosed with dyslexia by comparing our results to those of previous findings with adolescent and adults with dyslexia. However, our ability to make comparisons and draw conclusions was substantially limited by the lack of direct comparison in this study, the vast and inconsistent array of reading, attention, and WM measures used across studies, and the scarcity of research conducted in this area in adults with dyslexia. Future research investigating the cognitive abilities of HRD students would benefit from the inclusion of a comparison group consisting of university students diagnosed with dyslexia.

Second, we administered only one measure of reading comprehension, the Nelson-Denny Reading Test (NDRT); however, different reading comprehension measures vary in processing and storage demands and do not measure a unitary construct tapping the same cognitive processes (Cutting & Scarborough, 2006; Keenan et al., 2008). Therefore, the relationships of reading comprehension with attention and WM may vary with the reading comprehension measures used (Kendeou et al., 2012). For instance, previous work in normally developing children has found that WM may differentially predict reading comprehension performance on measures with different types of text (e.g., expository but not narrative; Wu et al., 2020) and only on reading comprehension questions with inferential demands (e.g., Potocki et al., 2017). The reading comprehension measure used in the present study included short, expository texts; however, it also included an equal number of literal and inferential questions. The inclusion of literal questions may have diminished the contributions observed between reading comprehension and attention and WM. Future studies aimed at replicating our findings and better understanding the relationships between reading and attention and WM should consider including multiple measures of reading comprehension with an array of different processing and storage demands.

An important topic for further evaluation is how the relationships between attention, WM, and both decoding and reading comprehension vary by reading history. Our findings from examining those relationships in HRD and NRD students, separately, suggest that differences exist between the two groups. Follow-up check analyses examining the moderating effects of reading history group on the relationships between reading and attention and WM provided support for some but not all the proposed group differences identified in the separate HRD and NRD analyses. The results from the follow-up analyses must be interpreted with caution, however, as our sample had insufficient power to detect very small interaction effects typical of categorical moderators (Aguinis et al., 2005). The current study represents an important first step towards identifying whether the relationships between reading skills and attention and WM performance are different in HRD university students than their NRD. It will be important to explore this topic more directly with adequately powered studies.

2.4.5 Summary and Conclusions

This study contributes to previous research documenting areas of challenge for university students with a history of reading difficulties (e.g., Deacon et al., 2012; Kemp et al., 2009; Metsala et al., 2019; Parrila et al., 2007). It replicated previous findings on HRD students' decoding and reading comprehension abilities (eg., Deacon et al., 2012) and self-reported difficulties maintaining their attention on academic tasks (Bergey et al., 2017). It also extends the characterization of this academically vulnerable group's abilities to the objective measure of their attention and WM functions, whereby HRD students demonstrated lower performance than their NRD peers on aspects of attention (i.e., vigilance decision speed, orienting, and inhibitory control of attention) and WM executive processes. HRD students appear to have attention and WM challenges similar to, but less extensive than those previously identified in adolescents and adults diagnosed with dyslexia (e.g., Buchholz & McKone, 2004; Horowitz-Kraus & Breznitz, 2009; Kapoula et al., 2010; Smith-Spark et al., 2003; Smith-Spark & Fisk, 2007). These results may indicate that HRD students and adults diagnosed with dyslexia may represent the same underlying population (Deacon et al., 2012) that exists along a continuum (Crisp & Lambon Ralph, 2006).

This study also contributes to previous research documenting the cognitive predictors of reading performance (e.g., Arrington et al., 2014; Christopher et al., 2012; Hannon, 2012). Across both groups (i.e., when combined), response inhibition was associated with better decoding performance. In the NRD group, successful and efficient decoding ability was associated with greater ability to remain vigilant/on-task and to quickly make decisions, and better decoding and reading comprehension was associated with WM performance in the verbal domain. In contrast, in the HRD group, only WM was significantly related to reading performance and these relationships were not restricted to one domain (i.e., both visuospatial and verbal). Group differences in the observed patterns of relationships between reading skills and attention and WM performance indicate that differences in academic skill proficiency and/or cognitive processes may affect the underlying relationships amongst those functions and that it is inappropriate to assume relationships observed in non-clinical skilled adult learners extend to adults with academic and/or cognitive challenges. Overall, the results of this study highlight the need for more research on the relationships between reading and cognitive functions in a variety of adult samples. They also further highlight the need to support HRD university students and indicate that WM, in both the visual and verbal domains, may be a promising target of intervention for them. Lastly, the results of this study highlight the importance of the central executive component of WM in reading and have implications for the inclusion of WM and controlled attention in theoretical models of reading.

Table 2.1

Demographic information of HRD (n=51) and NRD (n=51) participants

	NRD	HRD	Group Comparisons
Age (years)	20.14 (1.27)	19.67 (1.73)	$p = .12$ [a]
Education (years)	13.76 (0.89)	13.35 (1.28)	$p = .06$ [a]
# of Females	45	36	$p = .03$ [b]
# Using Anti-Depressant/ Anxiety Medication	2	3	$p = .64$ [b]
# Using Stimulant Medication	0	4	$p = .04$ [b]

Note: Standard deviation in brackets, a- Welch's independent samples t-test, b- chi-square test

Table 2.2

Descriptions of Reading Measures and the Variables Used from Each Measure

Measure	Description	Variables Used for Analyses
The Test of Reading Efficiency (TOWRE; Torgesen et al., 1999)	Single Word Efficiency (TOWRE-SWE) subtest: a measure of single word reading efficiency. Participants are presented with a list of 104 real words on a paper and they are asked to read as many items as they can in 45 seconds.	Total number of correctly pronounced items
	Phonemic Decoding Efficiency (TOWRE-PDE) subtest: a measure of phonemic decoding efficiency. Participants are presented with a list of 63 phonemically regular non-words on a paper and they are asked to read as many items as they can in 45 seconds.	Total number of correctly pronounced items
The Nelson-Denny Reading Test – Reading Comprehension (NDRT-RC; Brown et al., 1993)	A paper-and-pencil measure of reading comprehension and reading rate. Participants are given 20 minutes to read five short passages at a normal reading rate and respond to 38 factual and inferential multiple-choice questions about the passages. For reading rate, participants indicate what line of the first passage they have read to after the assessor notified them that a minute had passed.	Reading comprehension: Percent of correct answers (untimed reading comprehension; Deacon et al., 2006, 2012). This variable is calculated dividing the number of correctly answered questions by the number of attempted questions Reading rate: Amount of text read in one minute.

Table 2.3

Descriptions of Attention and WM Measures and the Variables Used from Each Measure

Measure	**Description**	**Variables Used for Analyses**
The Learning and Studying Strategies Inventory: Concentration Subscale (LASSI-Conc; Weinstein, 2002)	The LASSI is a 10-scale self-report measure that evaluates how aware a student is about learning and study strategies and their use of them. The LASSI-Conc subscale consists of 8-items that reflect a respondent's self-rated ability to direct and maintain their attention on academic tasks. Participants rate how well each statement describes them on a 5-point Likert scale. Ratings range from (a) – *not at all typical of me to* (e) – *very much typical of me*. Total raw scores can range from 8 to 40 with higher scores indicating more effective use of their concentration skills.	Total raw score
Dalhousie Computerized Attention Battery (DalCAB) – modified version	A battery of eight computerized tasks designed to measure different attention networks (i.e., vigilance/alerting, orienting, and executive control/attentional control; (Fan et al., 2002, 2005; Fernandez-Duque & Posner, 2001; S. A. H. Jones et al., 2016; Petersen & Posner, 2012). Reaction time and accuracy are recorded for each task. The tasks are described in detail in S. A. H. Jones et al. (2015) and include: Simple Reaction Time (SRT), Go/No-Go (GNG); Choice Reaction Time (CRT), Dual Task (DT); Vertical Flanker; Item Memory (IM), Location Memory (LM), and Visual Search (see Appendix K for a description of each task). The modified version of the DalCAB consists of 50% fewer trials for each subtest.	Eighteen variables from the modified version of the DalCAB were used for this research project. They were selected based on their loadings onto factors of vigilance, orienting, executive control/attentional control, and working memory (S. A. H. Jones et al., 2015). See Table 2.5 for a description of the selected variables and their factor groupings.

Measure	Description	Variables Used for Analyses
Operation Span Task (Engle, Kane, et al., 1999; modified from Kane et al., 2004)	A computerized verbal WM executive task (Kane & Engle, 2003), specifically a complex span task, that requires participants to study unrelated words for later recall alternating with an arithmetic task. Participants are presented with a math equation (e.g., “is (7x2)-1=14?”) and must read the equation out loud, say “yes” or “no” if the equation is correct, and press the corresponding “y” or “n” key on the keyboard. Fifty percent of the equations are correct. They are then presented with a word in the centre the screen for 1000ms that they must read out loud and try to remember. Following a 500ms delay, participants are presented with another equation question and word to remember, or a recall instruction. When presented with a recall instruction, participants must recall out loud all the words that they were presented in the block, in the order that they were presented, while the assessor records them. Each block of trials consisted of recall set sizes of 2, 3, 4, or 5 words. Participants practice the task twice at a set size of three. A total of 42 experimental trials are given across 12 blocks with three blocks of each set size presented in pseudorandom order.	The total number of words correctly recalled in the correct order position, summed across set sizes

Measure	Description	Variables Used for Analyses
Symmetry Span Task	A computerized visuospatial WM executive task (Kane & Engle, 2003), specifically a complex span task, that requires participants to remember the order of a series of red square locations in a matrix, alternating with making symmetry judgments. Participants are presented with an 8x8 matrix with black and white squares in the centre of the screen and must determine whether the filled black squares in the matrix were symmetrical across its vertical axis. They press the "y" key on the keyboard to indicate if the matrix is symmetrical or press the "n" key if it is not. Fifty percent of the matrices are symmetrical. Following their response and a 500ms delay, participants are presented with a 4x4 square matrix at the centre of the screen for 1000ms with one single red square. They must remember the location of the red square. Following a 500ms delay, participants are presented with another symmetry judgment trial and 4x4 matrix, or a recall instruction. When presented with a recall instruction, participants must recall the location of the read squares that they were presented in the block in the order that they were presented by marking them on answer sheets. Each block of trials consisted of two to five symmetry judgments and 4x4 matrices with a red square (i.e., set sizes 2, 3, 4, or 5). Participants practice the task twice at a set size of three. A total of 42 experimental trials are presented across 12 blocks; three blocks of each set size presented in pseudorandom order.	The total number of red square locations correctly recalled in the correct order position, summed across set sizes

Table 2.4

Performance on Assessment Measures By Group and By Factor

Factor	Variable	No History of Reading Difficulties (n=51) [a]	History of Reading Difficulties (n=51) [a, b]	Effect Size *d* (95%CI)	Group Comparison [c]
		M(SD)	*M(SD)*		
Reading	TOWRE SWE #Correct	94.8 (8.9)	89.7 (9.3)	.6 (.2, 1.0)	***p* = .006**
	TOWRE PDE #Correct	53.4 (7.2)	45.8 (10.4)	.9 (.4, 1.3)	***p* < .001**
	NDRT-RC – Reading Rate	276.9 (84.9)	250.7 (88.6)	.3 (-.1, .7)	*p* = .131
	NDRT-RC – % Correct	87.5 (9.0)	78.2 (13.1)	.8 (.4, 1.2)	***p* < .001**
-	Decoding Composite[d]	148.2 (14.7)	135.5 (18.1)	-	-
-	LASSI-Conc	29.3 (3.9)	25.2 (5.8)	.8 (.4, 1.3)	***p* < .001**
Vigilance: Processing Speed	Simple RT-RT[e]	278.66 (46.8)	269.1 (37.3)	-.2 (-.6, .2)	*p* = .258
	Simple RT-Prep Effect RT[e]	41.6 (45.8)	38.4 (38.6)	-.1 (-.5, .2)	*p* = .709
Vigilance: Decision Speed	Choice RT-RT[e]	401.1 (42.9)	425.2 (65.5)	.4 (.04, .8)	***p* = .031**[f]
	Feature Search-RT[e]	637.1 (81.1)	678.7 (104.5)	.5 (.05, .8)	***p* = .027**[f]
Orienting	Conjunction Search-RT[e]	1341.6 (220.2)	1449.4 (293)	.4 (.02, .8)	***p* = .038**[f]
	Conjunction Search-RT Slope	54.6 (24.7)	64.5 (35.6)	.3 (-.1, .7)	*p* = .107
AC: Switching/ Shifting	Dual Task Switch Cost-RT[e]	130.4 (81.3)	147.4 (87.2)	.2 (-.2, .6)	*p* = .312
	Dual Task Cost – RT[e]	141.8 (74.9)	117.4 (77.0)	-.3 (-.7, .1)	*p* = .110
AC: Interference Control/Conflict Resolution	Flanker Interference-RT[e]	56.3 (34.3)	67.9 (58.9)	.2 (-.2, .6)	*p* = .228
	Flanker Interference-%Error	2.6 (6.1)	1.5 (6.5)	-.2 (-.6, .2)	*p* = .402
AC: Response Inhibition	Go/No-Go-20% Go %FA	0.2 (1.0)	0.6 (1.0)	.4 (.03, .8)	***p* = .038**
	Go/No-Go-80% Go %FA	1.0 (1.4)	1.7 (2.2)	.3 (-.1, .7)	*p* = .108
WM Maintenance	Item Memory %Error	14.8 (9.1)	17.4 (8.9)	.3 (-.1, .7)	*p* = .145
	Location Memory %Error	20.0 (8.5)	22.0 (8.4)	.2 (-.2, .6)	*p* = .244
WM Executive	Operation Span Total	30.0 (5.5)	24.2 (7.1)	.9 (.5, 1.3)	***p* < .001**
	Symmetry Span Total	25.8 (7.2)	22.6 (7.5)	.4 (.04, .8)	***p* = .032**

Note: For the DalCAB tasks, only correct trials were included in the calculation of reaction time variables and all trials were included in the calculation of accuracy variables; AC=Attentional Control; FA=False Alarms; M=Mean; NDRT-RC=Nelson-Denny Reading Test – Reading Comprehension; RT=Reaction Time; SD=Standard Deviation; WM=Working Memory; a- n=48 for LASSI-Conc; b- n=50 for Simple RT - RT, Choice RT - RT, and Dual Task Cost - RT; c- Welch's t-test, d- TOWRE SWE+TOWRE PDE; e- milliseconds, f- no between-group differences in accuracy on the same measure ($p > .05$).

Table 2.5

Description of DalCAB Variables Used for Analyses

Network	Variable	Description
Vigilance: Processing Speed	SRT – Reaction Time (RT) SRT Preparation Effect - RT	▪ Mean RT across all trials ▪ (RSI 500ms RT – RSI 1500ms RT)
Vigilance: Decision Speed	CRT - RT Feature Search (FeatS) - RT	▪ Mean RT across all trials ▪ Mean RT on feature search trials averaged across set sizes
Orienting	Conjunction Search (ConjS) - RT ConjS – RT Slope	▪ Mean RT on conjunction search trials averaged across set sizes ▪ Slope of RT smallest set size to largest set size on conjunction search trials
Attentional Control: Switching/Shifting	DT Switch Cost - RT DT Cost - RT	▪ (Switch trials RT – No switch trials RT) on the choice reaction time task during the DT subtest ▪ (CRT task during the DT subtest RT - CRT subtest RT)
Attentional Control: Interference Control/Conflict Resolution	Flanker Interference (Flanker Int) - RT Flanker Int - %Error	▪ (Incongruent trials RT – Congruent trials RT) ▪ (Incongruent trials %Error – Congruent trials %Error)
Attentional Control: Response Inhibition	GNG – 20% Go - %False Alarms (FA) GNG – 80% Go - %FA	▪ Percentage of false alarms on 20% go frequency trials ▪ Percentage of false alarms on 80% go frequency trials
Working Memory Maintenance	IM - %Error LM - %Error	▪ Percentage of errors averaged across set sizes ▪ Percentage of errors averaged across set sizes

Table 2.6

Fixed Order Regression Results with Attention and WM Measures as Predictors and Decoding as the Outcome

Model	Predictor	Outcome: Decoding Composite			
		Group			
		NRD (n=51)[a]		HRD (n=51)	
		β	R^2	*β*	R^2
Model 1: Attention	Vigilance: Processing Speed Composite	.18		.05	
	Vigilance: Decision Speed Composite	-.58***		-.18	
	Orienting Composite	.17		.04	
	AC: Switch/Shifting Composite	.05		.00	
	AC: Interference Control/Conflict Resolution Composite	-.05		-.23	
	AC: Response Inhibition Composite	-.01		-.19	
			.26*		.14
Model 2: WM Maintenance	Item Memory %Error	-.43*		-.15	
	Location Memory %Error	.17		-.32*	
			.13*		.16*
Model 3: WM Executive	Operation Span Total	.54***		.32*	
	Symmetry Span Total	-.05		.10	
			.28***		.15*

Note: AC=Attentional Control; WM=Working Memory; a - n=50 for Simple RT - RT and Choice RT – RT within the vigilance composites, and Dual Task Cost – RT within the AC: Switch/Shifting Composite; * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 2.7

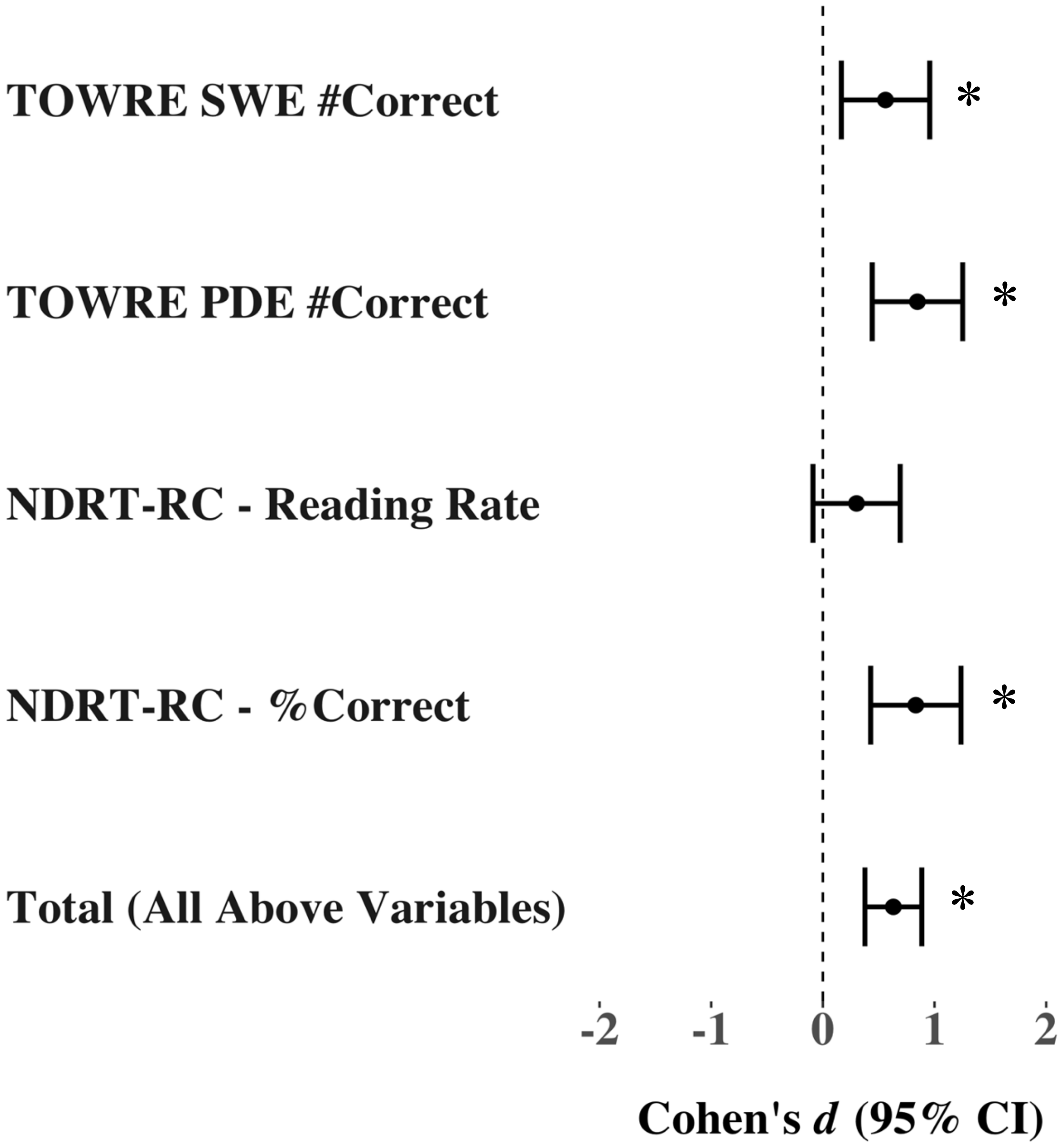
Fixed Order Regression Results with Attention and WM Measures as Predictors and Reading Comprehension as the Outcome

Model	Step	Predictor	Outcome: NDRT Reading Comp. %Correct			
			Group			
			NRD (n=51)[a]		HRD (n=51)	
			β	$\triangle R^2$	*β*	$\triangle R^2$
Model 1: Attention	1	Decoding Composite	.37*	.07	.32*	.13**
	2	Vigilance: Processing Speed Composite	-.13		.11	
		Vigilance: Decision Speed Composite	.27		-.05	
		Orienting Composite	.02		.11	
		AC: Switching/Shifting Composite	.00		-.06	
		AC: Interference Control/Conflict Resolution Composite	.09		-.19	
		AC: Response Inhibition Composite	.17		.07	
				.07		.04
Model 2: WM Maintenance	1	Decoding Composite	.29	.07	.24	.13**
	2	Item Memory %Error	.11		.14	
		Location Memory %Error	-.18		-.43**	
				.02		.14*
Model 3: WM Executive	1	Decoding Composite	.01	.07	.21	.13**
	2	Operation Span Total	.46**		.48**	
		Symmetry Span Total	.12		-.12	
				.20**		.16**

Note: The standardized beta coefficients are from the final step of the regression model; AC=Attentional Control; NDRT=Nelson-Denny Reading Test; WM=Working Memory; a - n=50 for Simple RT - RT and Choice RT – RT within the vigilance composites, and Dual Task Cost – RT within the EC: Switching/Shifting Composite; * $p < .05$, ** $p < .01$, *** $p < .001$.

Figure 2-1

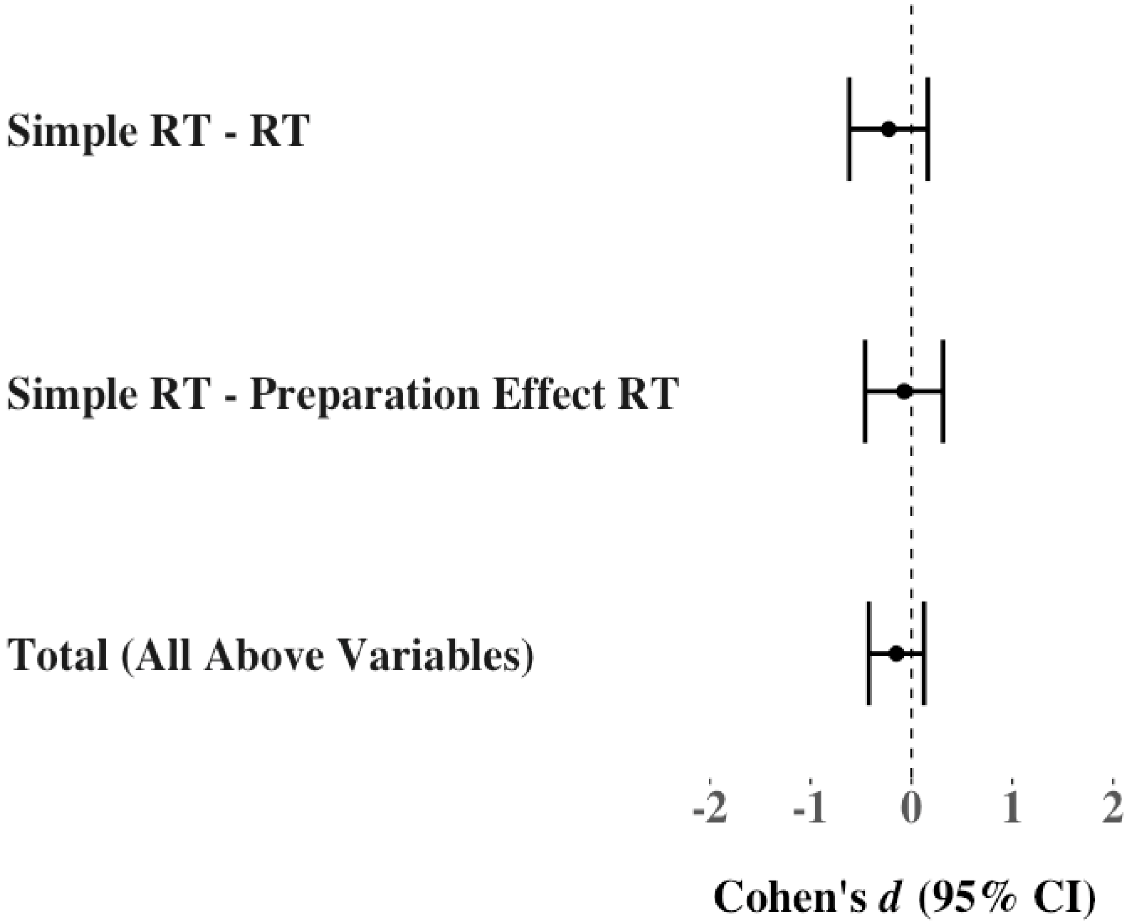
Forest plots of Cohen's d for the reading variables and factor



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., more items read on the TOWRE measures, faster reading rate on the NDRT-RC, and a greater percent of correct answers on the NDRT-RC). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). PDE= Phonemic Decoding Efficiency; RC=Reading Comprehension; SWE=Single Word Efficiency.

Figure 2-2

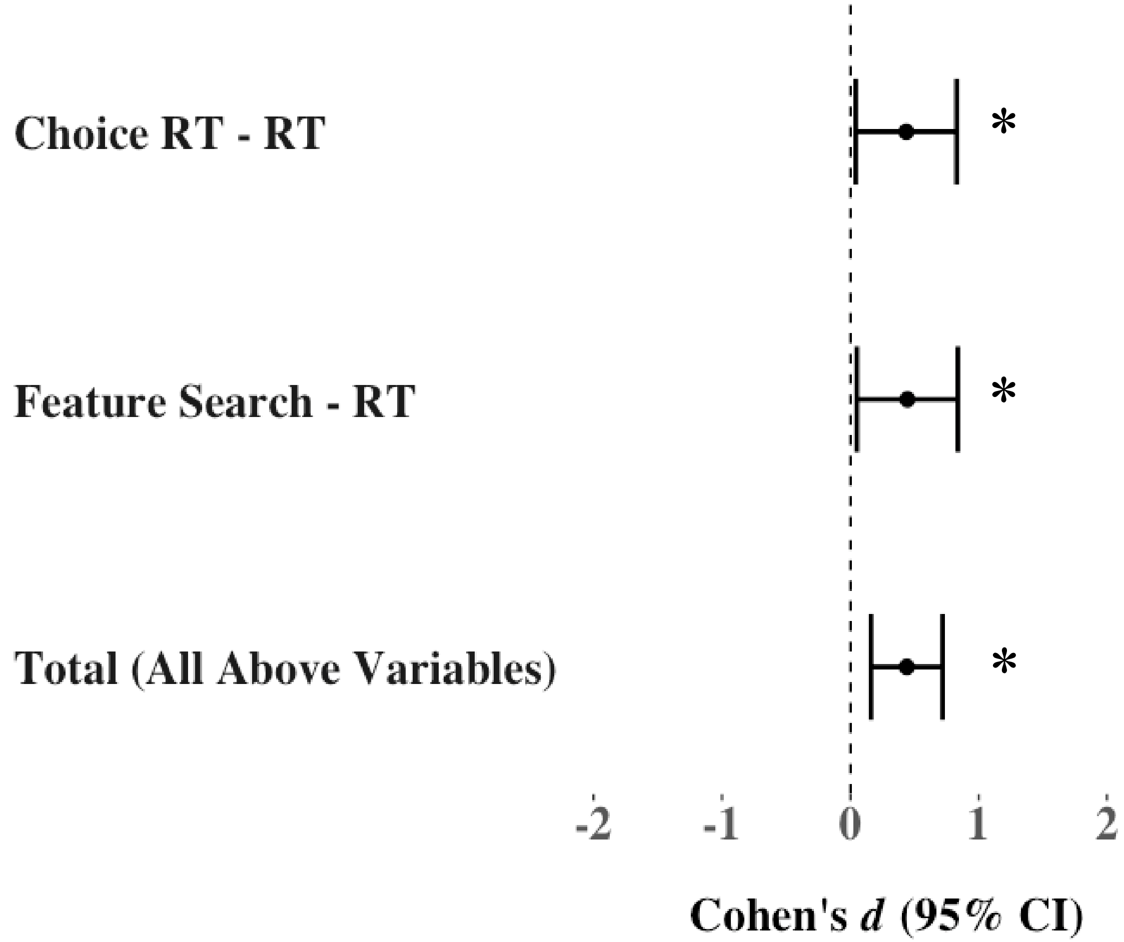
Forest plots of Cohen's d for the vigilance processing speed variables and factor



Note: Cohen's d to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., faster reaction times). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). RT=Reaction Time.

Figure 2-3

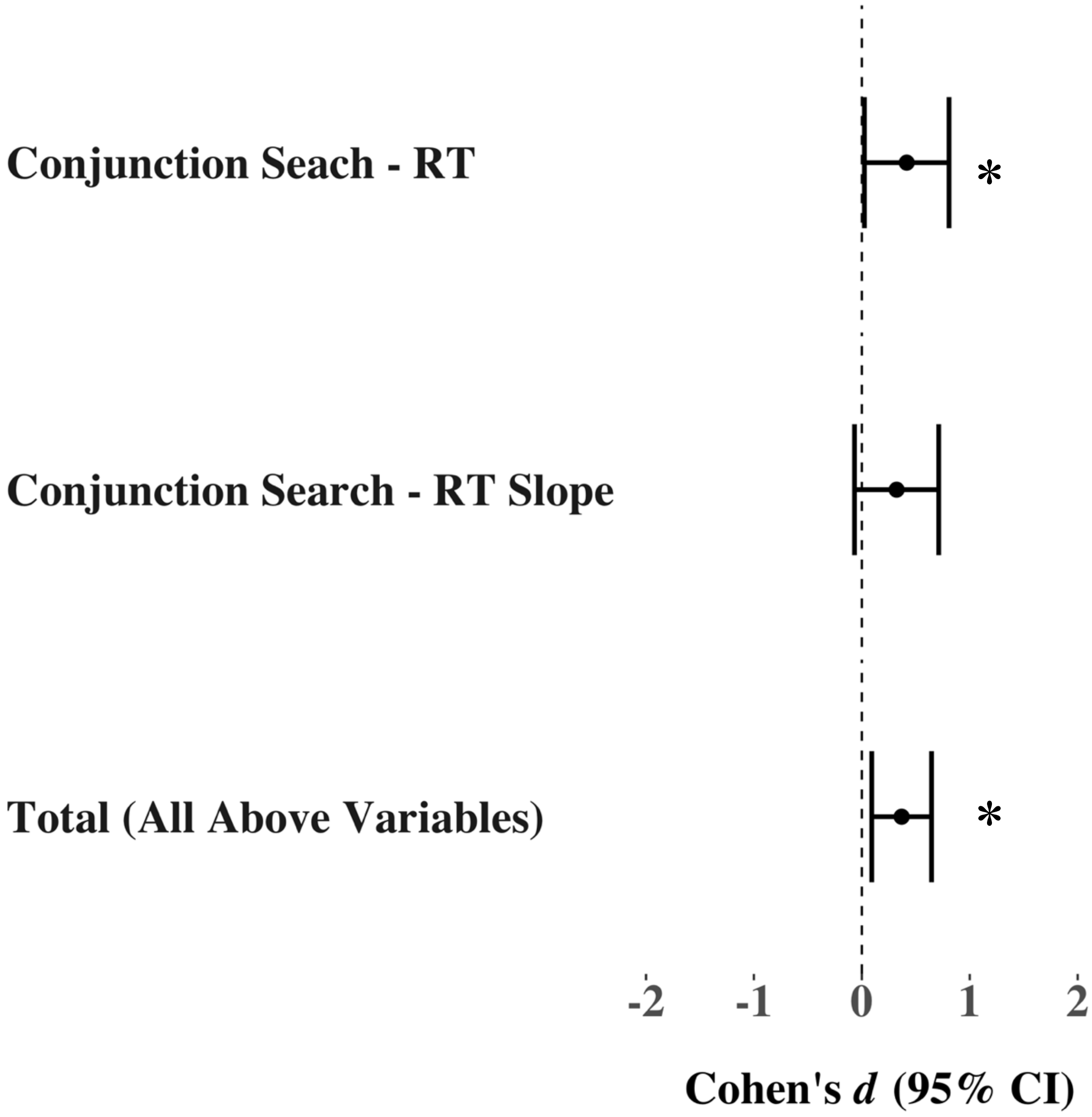
Forest plots of Cohen's d for the vigilance decision speed variables and factor



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., faster reaction times). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). RT=Reaction Time.

Figure 2-4

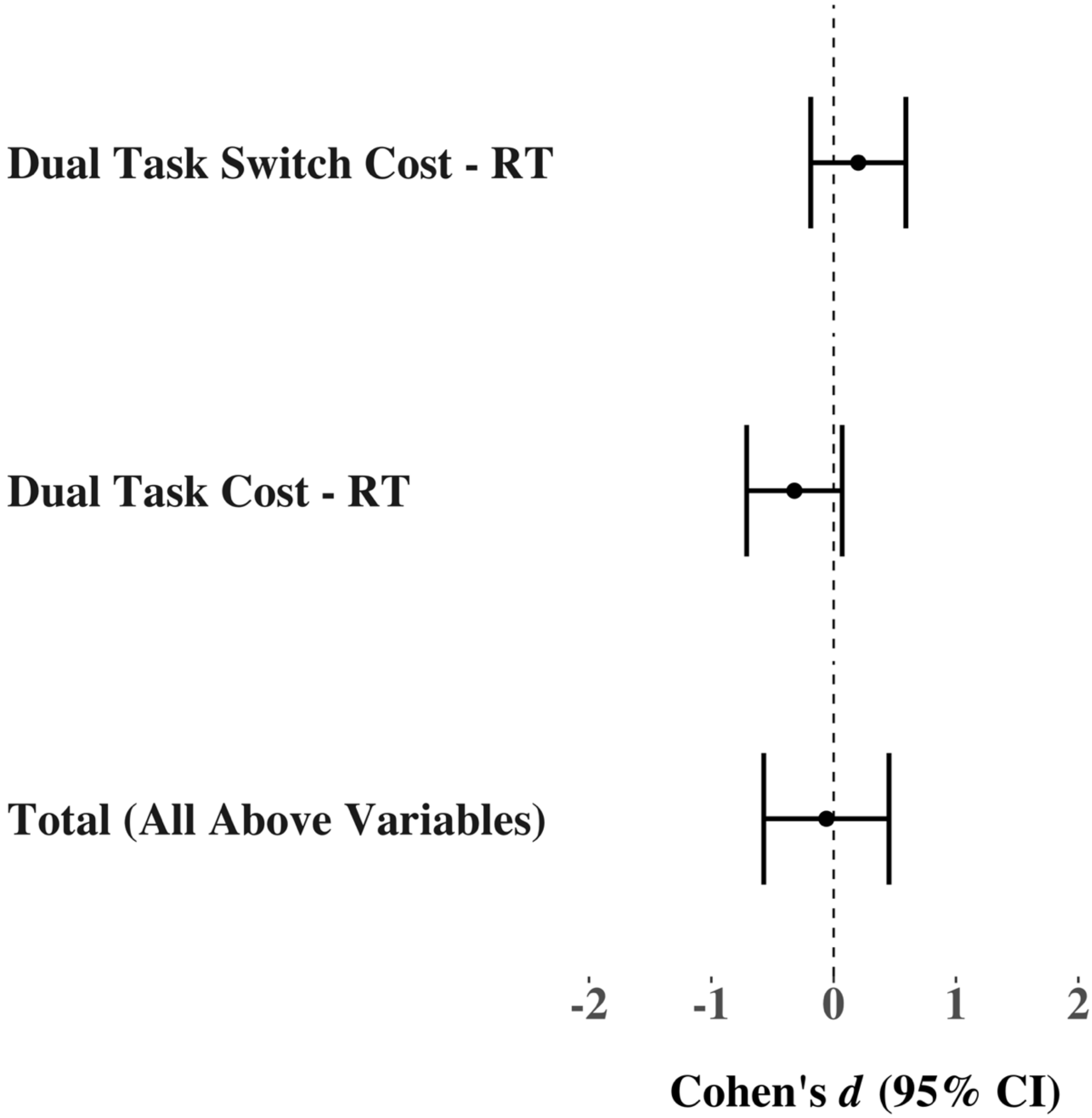
Forest plots of Cohen's d for the orienting variables and factor



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., faster reaction times and smaller RT slopes). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). RT=Reaction Time.

Figure 2-5

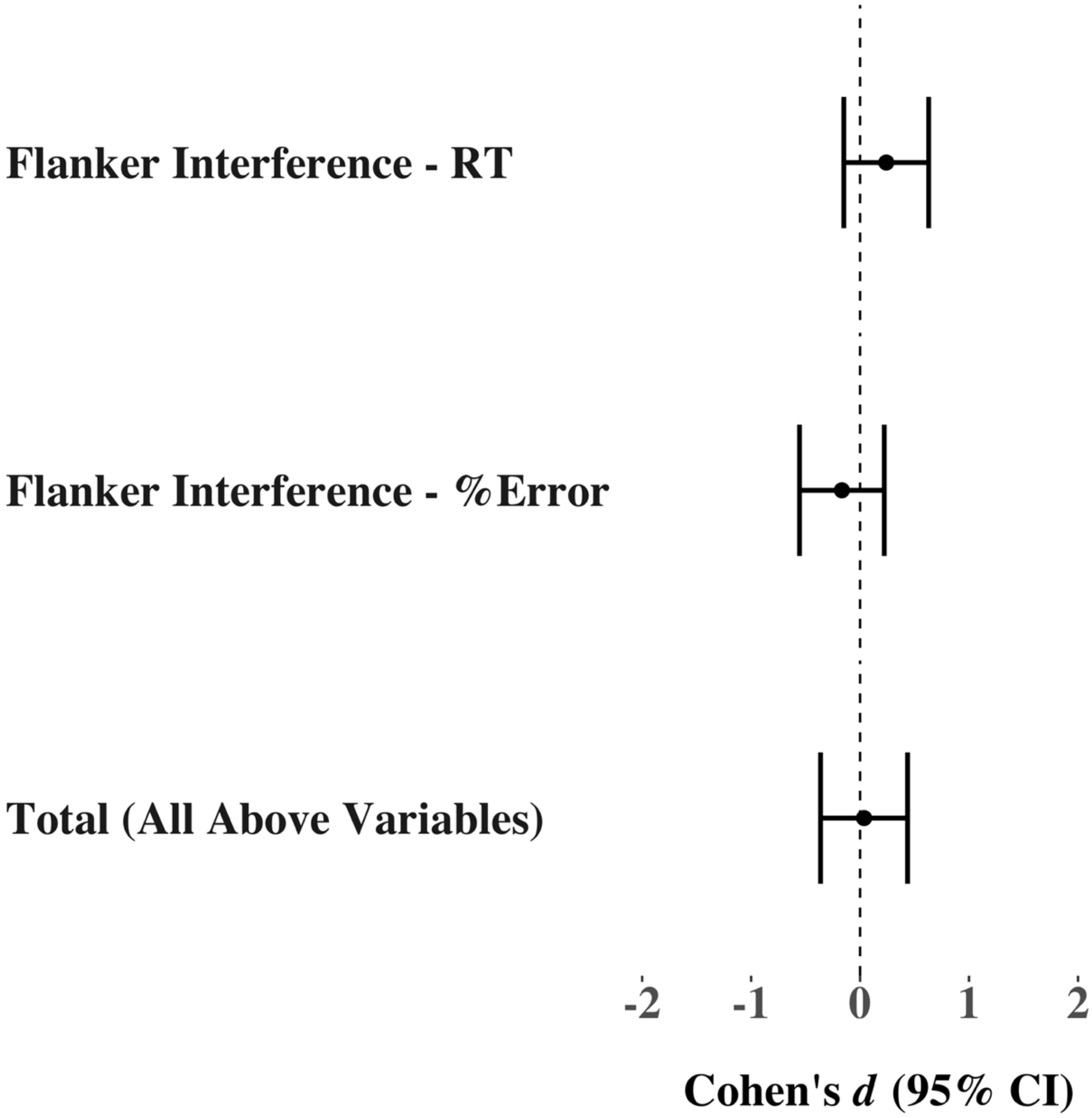
Forest plots of Cohen's d for the attentional control: switching/shifting variables and factor



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., faster reaction times and fewer error). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). RT=Reaction Time.

Figure 2-6

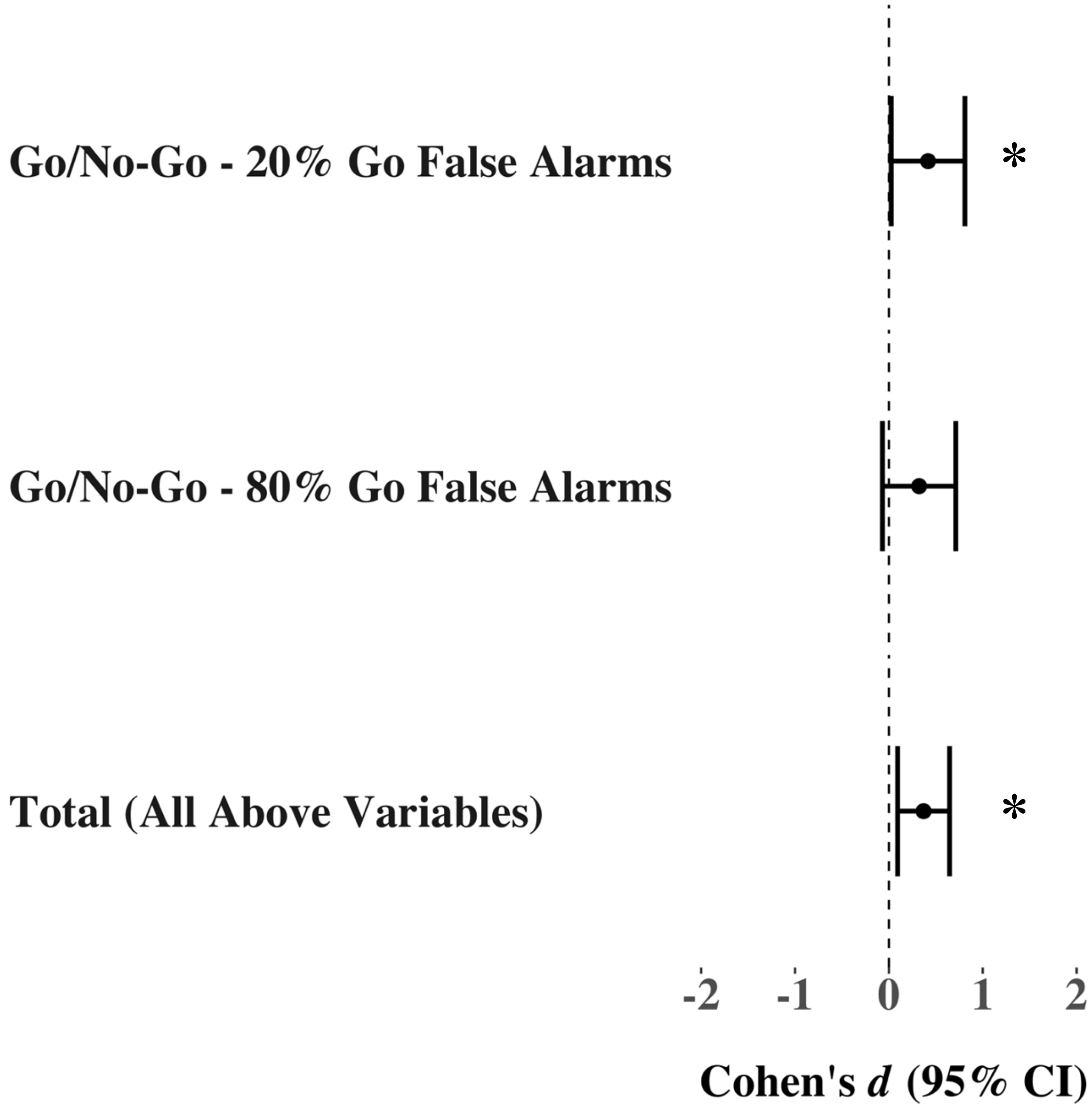
Forest plots of Cohen's d for the attentional control: interference control/conflict resolution variables and factor



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., faster reaction times and fewer error). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). RT=Reaction Time.

Figure 2-7

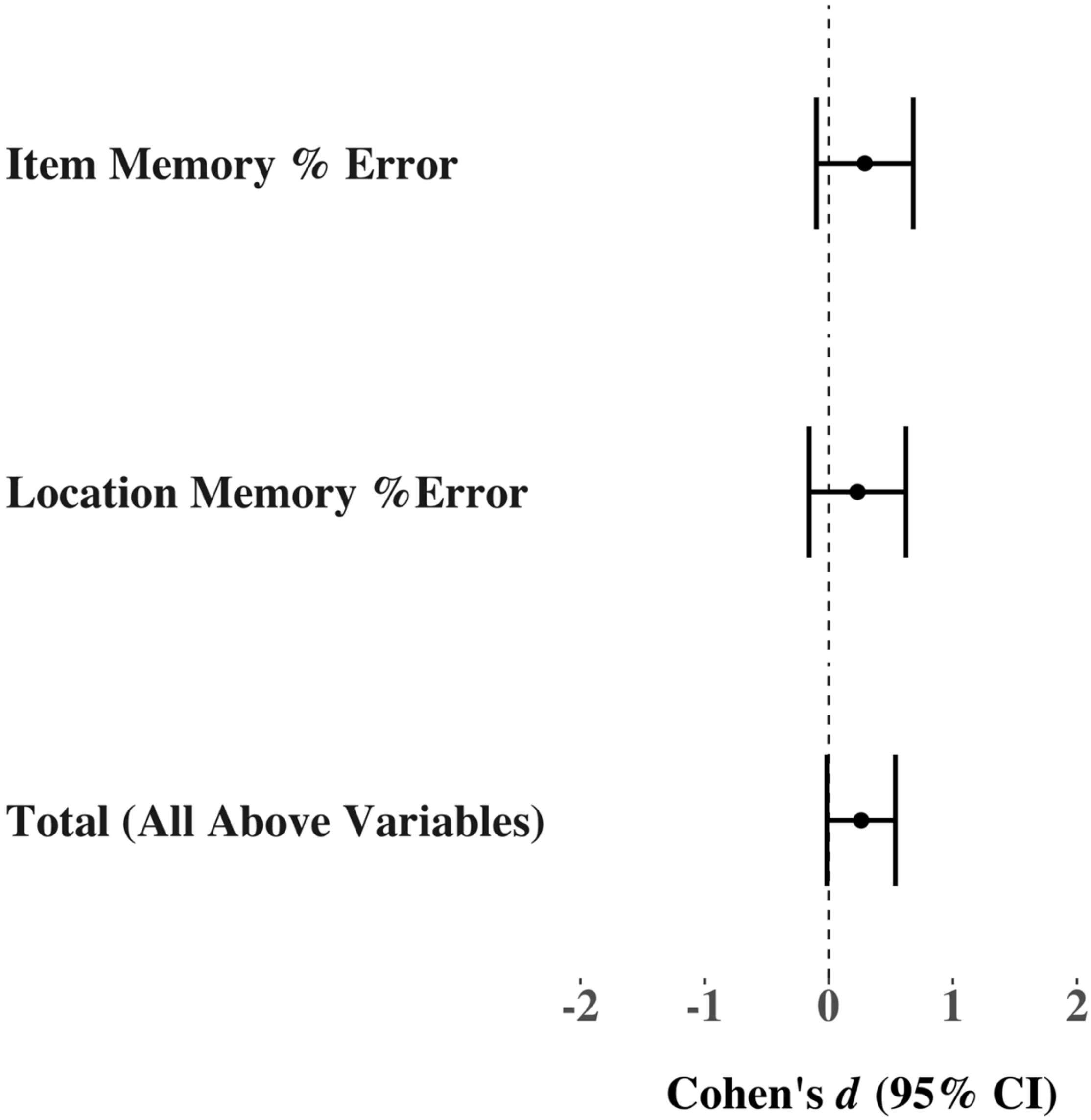
Forest plots of Cohen's d for the attentional control: response inhibition variables and factor



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., faster reaction times and fewer errors). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*).

Figure 2-8

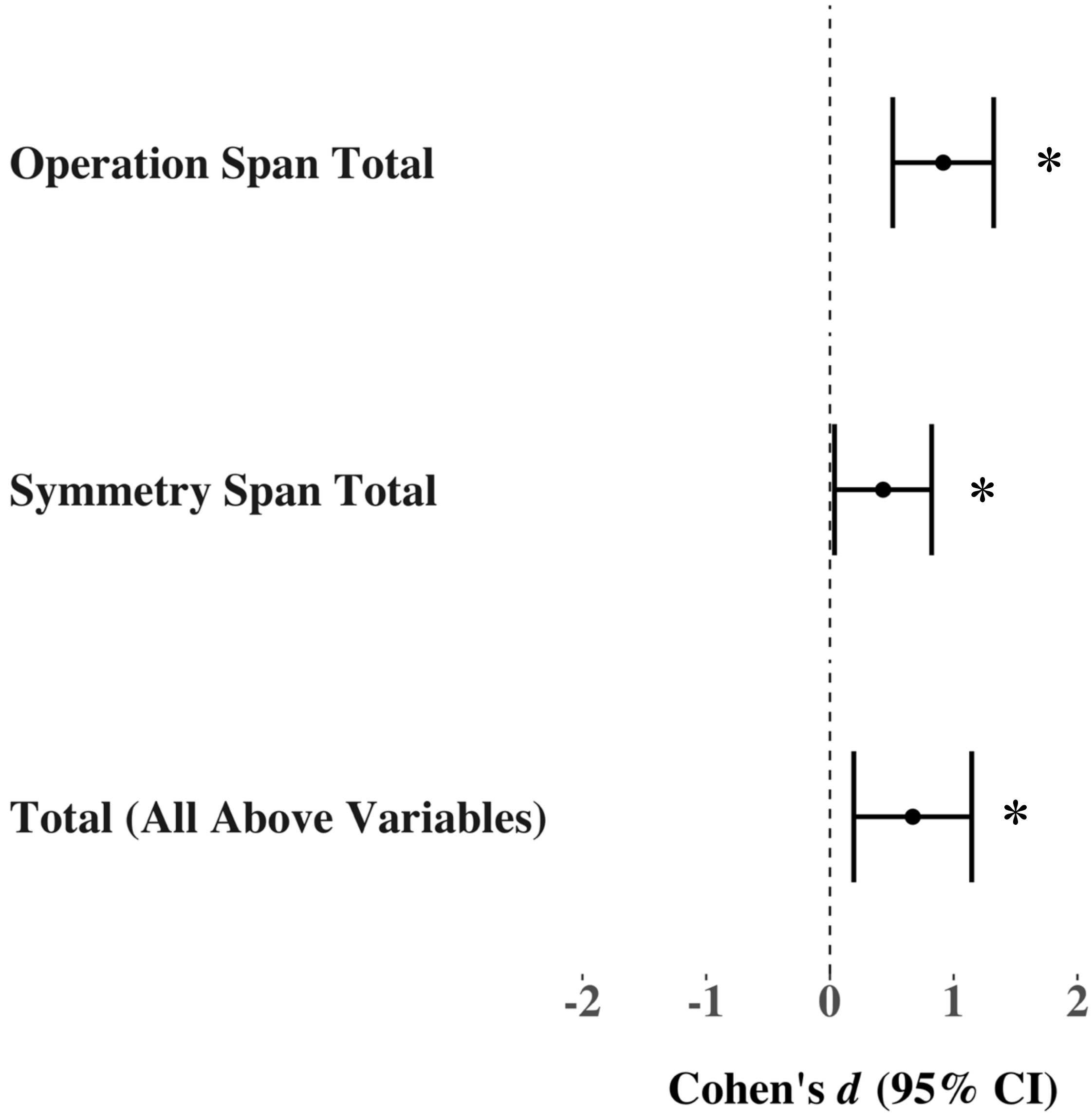
Forest plots of Cohen's d for the working memory maintenance variables and factor



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., fewer errors). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*).

Figure 2-9

Forest plots of Cohen's d for the working memory control variables and factor



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by NRD participants (i.e., greater total scores). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*).

Chapter 3: Study 2 – Computerized working memory training in undergraduate students with a history of reading difficulties

3.1 Introduction

Working memory (WM) has been found to play a critical role in new learning and the development of academic skills (for a review, see Dehn, 2008). It is a limited capacity short-term memory system involved in the maintenance and manipulation of information for in-the-moment use (Baddeley, 2012). Baddeley's multicomponent model of WM described WM as a system that contains domain-specific maintenance components that specialize in the temporary storage of specific types of information (i.e., the phonological loop and the visuospatial sketchpad), a passive buffer system that allows for the integration of information from WM and long-term memory and perception (i.e., the episodic buffer) and a domain-general attentional component responsible for the processing of information within WM from various sources (i.e., the central executive; Baddeley, 2012, 2021; Fenesi et al., 2015). WM is believed to be important for storing, processing, and integrating information during reading activities (for a review, see Dehn, 2008). In support of the involvement of WM in reading, several studies have found significant relationships between WM and reading growth (Larsen et al., 2022; Morgan et al., 2019; Stipek & Valentino, 2015; Swanson & Jerman, 2007) and between current WM and both decoding and reading comprehension performance (e.g., De Beni et al., 2007; Follmer, 2018; Hannon, 2012; Ober et al., 2020; Peng et al., 2018). Moreover, WM deficits have been identified as common features in the cognitive profiles of adults with reading problems (e.g., Ghani & Gathercole, 2013; Smith-Spark & Fisk, 2007; Vasic et al., 2008). Given these findings, targeting and improving WM could lead to improvements in reading performance. The current study sought to examine the potential benefits of computerized WM training in adults with persistent reading difficulties (Deacon et al., 2012) and academic challenges (Bergey et al., 2017; Chevalier et al., 2017), specifically, university students with a history of reading difficulties (HRD).

Over the last several decades, an increasing number of individuals with learning difficulties have been attending post-secondary institutions (Henderson, 2001; Learning Disabilities Association of Ontario, 2018; Nichols et al., 2002). HRD students self-identify as having early reading difficulties by means of their responses to a questionnaire (i.e., Adult Reading History Questionnaire – Revised; Parrila et al., 2003) and make up 10% to 30% of students in Canadian universities (Bergey et al., 2017; Chevalier et al., 2017; Deacon et al., 2017). Although HRD students are able to cope and compensate with their early reading difficulties enough to achieve university admission (Deacon et al., 2012; Metsala et al., 2019), they experience academic challenges in post-secondary education, earning lower GPAs on average and completing fewer course credits than their peers without a history of reading difficulties (NRD; Bergey et al., 2017; Chevalier et al., 2017). Moreover, on average, HRD university students continue to have persistent difficulties in decoding (i.e., oral reading of written words and non-words with accuracy and/or fluency) and reading comprehension, and to have weaknesses in language and literacy-specific processes relative to their peers without histories of reading difficulties (NRD; Al Dahhan et al., 2014; Deacon et al., 2012; MacKay et al., 2019; Metsala et al., 2019; Parrila et al., 2007; see Appendix B for summary of research findings on HRD students' reading skills). Unfortunately, most HRD students do not have access to specific academic accommodations and have consequently been identified as an academically vulnerable group (Bergey et al., 2017; Chevalier et al., 2017).

Weaknesses in WM may underly HRD students' reading difficulties and may thus be a good target for intervention to support them. In Study 1, we investigated HRD students' attention and WM abilities and the relationships between those abilities and the reading performance of HRD and NRD students. To our knowledge, this was the first study to do so in HRD students. Relative to their NRD peers, HRD students demonstrated weaknesses on measures of vigilance decision speed, orienting attention, and response inhibition, as well as on verbal and visuospatial WM measures that placed high demands on the attentional control component of WM (i.e., WM executive tasks). Notably, there were no group differences found on measures that rely primarily on the domain-specific storage systems of WM (i.e., WM maintenance tasks). We also found that the maintenance and attentional control components of WM were both significantly related to HRD decoding and reading comprehension. Those relationships were not limited to a specific domain, with HRD reading performance showing significant associations with measures of WM processing of both visuospatial and verbal information. Importantly, we found that only a WM executive task was reliably associated with reading performance in both HRD and NRD students. The findings from Study 1 provided support for the involvement of WM in adult reading performance and that HRD students' reading difficulties may be due, at least in part, to weaknesses in the attentional control component of WM. The results also indicated that an intervention aimed at improving WM, in both the visual and verbal domains, may be one avenue for improving HRD students' reading skills.

The use of computer-based WM training to improve WM functioning and related functions has emerged as a popular area of research over the past 20 years. Training typically involves the intensive, repetitive practice of adaptive WM tasks. Challenging the flexibility of the WM system through training is theorized to promote cognitive plasticity (Lövdén et al., 2010). Compared to controls, WM training has been found to enhance functional connectivity in frontoparietal regions of the brain involved WM task performance (e.g., Langer et al., 2013) and to improve the structural connectivity of white matter in those regions (e.g., Dziemian et al., 2021). According to the capacity-efficiency model of transfer, WM training is theorized to result in behavioural gains on untrained tasks as the result of training-induced gains in the amount of information that can be held and processed in WM (i.e., WM capacity) and/or to optimize WM performance within the current limits of the system (i.e., WM efficiency; von Bastian et al., in press; von Bastian & Oberauer, 2014). Increases in WM capacity and/or efficiency are expected to result in gains on tasks that draw on WM capacity resources or on tasks on which knowledge, strategies, or automatized basic processes or cognitive routines acquired from training can be applied (Gathercole et al., 2019; von Bastian & Oberauer, 2014).

Using pretest–posttest designs, many studies have demonstrated performance gains in WM and related functions following WM training. Meta-analyses of such studies have found evidence for significant small to large immediate gains on untrained WM tasks, commonly referred to as near transfer effects (Melby-Lervåg et al., 2016; Melby-Lervåg & Hulme, 2013; Schwaighofer et al., 2015; Soveri et al., 2017). Researchers have also evaluated whether the benefits of WM training can extend to abilities that involve WM processes (i.e., far transfer). The most frequently investigated far transfer effects to date have been to measures of fluid intelligence and cognitive control (e.g., Carretti et al., 2013; Chein & Morrison, 2010; Jaeggi et al., 2008; Klingberg et al., 2005). Most meta-analytic reviews have identified small far transfer effects to fluid intelligence (e.g., Au et al., 2015; Soveri et al., 2017) and cognitive control (e.g., Melby-Lervåg & Hulme, 2013; Soveri et al., 2017). Of particular relevance to the current study, a meta-analysis by Melby-Lervåg et al. (2016) identified small far transfer effects to reading comprehension (g = 0.12 to 0.15) but no transfer effect to decoding (g = 0.01 to 0.08) in children to young adults. Whereas inconsistencies in results (perhaps due to differences in meta-analytical choices) have inspired heated debates regarding the generalizability of WM training effects (Au et al., 2016; Melby-Lervåg & Hulme, 2016); evidence for far transfer, however small, is encouraging and warrants further investigation.

With respect to far transfer to reading outcomes from WM training, most studies have been conducted in samples of typically developing children (Artuso et al., 2019; Fälth et al., 2015; Henry et al., 2014; J. S. Jones et al., 2020; Karbach et al., 2015; Loosli et al., 2012; Sánchez-Pérez et al., 2018; Söderqvist & Nutley, 2017) and in children with attention or WM deficit or learning difficulties (Chacko et al., 2014; K. I. E. Dahlin, 2011; Dunning et al., 2013; Egeland et al., 2013; Gray et al., 2012; Holmes et al., 2009; Partanen et al., 2015). Moreover, most studies have trained children on tasks that rely primarily on the domain-specific storage systems of WM (hereafter referred to as WM maintenance tasks), such as the forward and backwards span tasks from Cogmed, a popular commercial WM training program (Klingberg et al., 2005). A minority have trained children on tasks that place greater demands than WM maintenance tasks on the attentional control system of WM (hereafter referred to as WM executive tasks) such as complex span paradigms (e.g., Henry et al., 2014; Loosli et al., 2012) and *n*-back tasks (Sánchez-Pérez et al., 2018) or other tasks involving WM updating processes (Artuso et al., 2019). Transfer to measures of decoding and reading comprehension of simple sentences has generally not been observed in children following up to 18.75 hours of WM training (e.g., Chacko et al., 2014; Gray et al., 2012). In contrast, transfer has been observed to measures of reading comprehension of passages with the strongest support for transfer following training on tasks placing high demands on the attentional control system of WM (hereafter referred to as WM executive tasks; Artuso et al., 2019; K. I. E. Dahlin, 2011; Egeland et al., 2013; Henry et al., 2014)

Studies have also evaluated transfer to reading outcomes in adults following training on WM executive tasks with mixed results (see Appendix F for a summary of study characteristics and training effect on reading outcomes in adults). Using adaptive complex span tasks as training tasks, Chein and Morrison (2010) and Redick et al. (2020) both evaluated transfer to reading comprehension of passages in young adults without known cognitive impairments or learning difficulties. Both groups of researchers used the Nelson-Denny Reading Test as to measure reading comprehension of passages. Following 10 to 15 total hours of training on both a verbal complex span task and a visuospatial complex span task, Chein and Morrison found evidence in favour of transfer compared to passive controls. In contrast, following five hours of training on a single verbal complex span task, Redick et al. found no evidence in favour of transfer compared to active controls. Although the authors' choices of control group might be responsible for their conflicting results, other study characteristic such training stimulus domains (i.e., verbal, visuospatial, or both) and training dose could have also impacted the effectiveness of their WM training programs (Pappa et al., 2020; Schwaighofer et al., 2015). In another study, Thompson et al. (2013) trained a community sample of healthy adults between 18 and 45 years of age (*M* = 21.2) on an adaptive dual *n*-back task. Like Chein and Morrison, Thompson et al.'s training programs included both verbal and visuospatial stimuli but at a lower training dose (i.e., approximately 8.33 total hours). Thompson et al. found no evidence of transfer to the Nelson-Denny Reading Test compared to active control groups; however, participant baseline performance on the reading comprehension measure was at or near ceiling, thus limiting the measure's sensitivity to performance gains. WM training may be less effective for individuals with high baseline skills and may be more beneficial for those with baseline deficits or weaknesses, like those with cognitive or learning difficulties (Au et al., 2015; Holmes et al., 2009; Jaeggi et al., 2008; Klingberg et al., 2005). Thus, inconsistencies in findings across WM training studies in unimpaired adults may be consequent to the type of control group used as well as differences in intervention and participant characteristics.

To our knowledge, only two studies have investigated the far transfer effects of WM training to reading outcomes in young adults with cognitive and/or learning difficulties (see Appendix F). Unfortunately, neither included WM executive tasks as training tasks, which have the strongest support for transfer to reading comprehension of passages in children (Artuso et al., 2019; Henry et al., 2014). Gropper et al. (2014) and Shiran and Breznitz (2011) both evaluated the transfer-effects of training on short-term memory and WM maintenance training tasks in impaired learners. Gropper et al. found no evidence in favour of transfer to reading comprehension of passages in a sample of undergraduate students with ADHD and/or learning disabilities following 18.75 hours of training with Cogmed. In contrast, Shiran and Breznitz found that both impaired and skilled university student readers improved from pre-training to post-training on measures of decoding, reading rate, and reading comprehension following six hours of training with the CogniFit Personal Coach training program but not following training on an active control task. Unfortunately, the authors did not directly compare the training and control groups, thus limiting the strength of the conclusions that could be drawn from their results. Despite their lack of direct comparison to an active control group, Shiran and Breznitz's findings, along with Chein and Morrison's, provide initial support for the potential for WM training to aid reading performance in adult populations.

3.1.1 Summary and Rationale

In summary, HRD undergraduate students have been identified as an academically vulnerable group of students in need of support (Bergey et al., 2017; Chevalier et al., 2017). Despite most not having a formal diagnosis of a learning disability, HRD students present with many of the same challenges in reading as their peers with documented learning disabilities or dyslexia (Deacon et al., 2012). Weaknesses in WM, a higher-order cognitive system whose storage and attentional control functions are believed to be involved in reading (for a review, see Dehn, 2008), may play an important role in HRD students' ongoing reading difficulties. In Study 1, we found that HRD students have reading, attention, and WM weaknesses, relative to their NRD peers, and we found that HRD students' WM performance was significantly related to their reading performance on measures of decoding and reading comprehension of passages. Given the identified relationships between WM and reading in HRD students, improving WM should theoretically result in gains in HRD students' reading performance.

Computerized WM training has been identified as having the potential to improve WM functioning and to improve functions that involve WM or that share common processes with WM. Meta-analytical reviews have found empirical evidence for significant small to large immediate near transfer effects to untrained WM tasks and small far transfer effects outcomes related to WM performance (Au et al., 2015; Melby-Lervåg et al., 2016; Melby-Lervåg & Hulme, 2013; Schwaighofer et al., 2015; Soveri et al., 2017). To date, the strongest empirical support for far transfer from WM training to reading outcomes has been for transfer to reading comprehension of passages following training on tasks that place high demands on the attentional control system of WM (Artuso et al., 2019; Chein & Morrison, 2010; K. I. E. Dahlin, 2011; Egeland et al., 2013; Henry et al., 2014). Previous evidence that WM training can improve reading performance offers support for the idea that WM training may be utilized as an intervention to improve reading in HRD university students; however, transfer effects could vary as a function of individual differences (e.g., age and baseline cognitive ability), the training paradigm used, and intervention-specific factors (e.g., intensity and duration; von Bastian & Oberauer, 2014). Thus, it is critical that we study the effects of WM training specifically in HRD students.

3.1.2 Study 2

The main objective of Study 2 was to evaluate the effects of WM training on WM functioning and reading abilities in HRD undergraduate students. To achieve this, HRD participants were randomly assigned to a WM training group or an active control group. The WM training program was an adaptive dual *n*-back task. The *n*-back task is one of the most widely used WM executive paradigms used in WM training studies and it has been associated with improvements on untrained WM, fluid intelligence, and cognitive control tasks (Soveri et al., 2017). The adaptive dual *n*-back task used in this study involved the simultaneous presentation of auditory and visual stimuli. The active control group was given a non-adaptive version of the same training task that remained at an *n*-level of one. Pre- and post-training measurements of verbal and visuospatial WM, decoding, and reading comprehension of passages were administered to both groups. We also included a pre- and post-training measure of self-reported attention on academic tasks because we were interested in whether training on a WM task would lead to subjective attentional control-related functional improvements in the academic setting. Using the same measure as the one used in the current study, previous research has found that HRD students self-report having more difficulty than NRD students at maintaining their attention on academic tasks (Bergey et al., 2017; Study 1).

The present study is the first to test the effectiveness of WM training in a sample of young undergraduate adults with weaknesses in reading. We based our hypotheses on previous findings in samples of children and adolescents with learning difficulties and/or weaknesses in attention and/or working memory (e.g., Alloway et al., 2013; Dunning et al., 2013; Gray et al., 2012; Holmes et al., 2009), as well as in non-clinical samples of adults (Pappa et al., 2020; Soveri et al., 2017). We hypothesized that compared to the active control group, the WM training group would show significant improvements on related but untrained WM tasks. Further, we hypothesized that we would find specific training-related benefits in the training group and not in the active control group for reading comprehension of passages but not decoding.

3.2 Methods

3.2.1 Participants

A total of 42 university students with a history of reading difficulties (HRD) between the ages 17 and 24 years old were recruited from Study 1 (M_{Age} *(SD)* = 19.58 (1.76); 27 female). HRD classification was determined based on individuals' proportion scores on the elementary school subscale of the Adult Reading History Questionnaire-Revised (ARHQ-R; see Appendix A); as in previous studies, individual with scores of .37 or greater were categorized as HRD (Deacon et al., 2012; Parrila et al., 2007). Having met the eligibility criteria in Study 1, all participants self-reported English as their first language (both spoken, reading and writing), normal or corrected to normal vision, no history of head injury with loss of consciousness for more than five minutes, no current diagnosis of a severe neurological or psychiatric disorder, and no commencement or change in dose of a psychotropic medication within four weeks of beginning the study.

Participants were randomly assigned in blocks of six with replacement to one of two groups, a WM training group or an active control group (see Table 3.1 for a summary of sample demographics). Group allocation concealment was achieved using sequentially numbered opaque envelopes. One participant in the active control group and two participants in the WM training group reported receiving an earlier diagnosis of Attention Deficit Hyperactivity Disorder (i.e., ADHD), and one participant in the WM training group reported receiving a diagnosis of a learning disability in elementary school but did not specify the type. There were no differences between the active control group and the WM training group with respect to age, years of education, gender, and ARHQ-R proportion score.

3.2.2 Measures

3.3.2.1 Self-Reported Attention on Academic Tasks.

3.2.2.1.1 The Learning and Studying Strategies Inventory (LASSI): Concentration Subscale. The LASSI Concentration Subscale (LASSI-Conc) is a self-report measure of attention as it relates to academic tasks (see Table 3.2 for a description of the measure and the variable used for analyses). The LASSI-Conc has been shown to have strong internal consistency (α = .84) and test-retest reliability (r = .85; Weinstein, 2002). Overall, the LASSI has been shown to be able to differentiate academically successful university students from unsuccessful ones (Marrs et al., 2009). Furthermore, individual LASSI scales and latent factors within the measure have been found to be good predictors of academic performance (Cano, 2006; Marrs et al., 2009; Seabi, 2011; West & Sadoski, 2011).

3.2.2.2 Working Memory. See Table 3.2 for a detailed description of each measure and the variables used from each measure for the analyses.

3.2.2.2.1 The Dalhousie Computerized Attention Battery (DalCAB) - Modified Version. The DalCAB contains eight subtests designed to measure attention and WM. Performance on the DalCAB has been shown to have good test–retest reliability (r=.71–.87) and validity (S. A. H. Jones et al., 2015, 2016). Only the Item Memory and Location Memory subtests (i.e., measures of WM maintenance) were used for the purposes of this study. The other six subtests were administered to participants as part of Study 1; however, the data from those measures will not be reported here.

3.2.2.2.2 Operation Span Task. The Operation Span (Engle, Kane, et al., 1999; modified from Kane et al., 2004) is a computerized verbal measure of WM executive processes (Kane & Engle, 2003). It has been shown to have strong internal consistency (α = .84–.86; Engle, Tuholski, et al., 1999; Kane et al., 2004; Redick et al., 2012; Unsworth et al., 2005) and test–retest reliability (r = .83; (Redick et al., 2012; Unsworth et al., 2005). It has also been shown to converge with other complex span measures (r=.55–.73; Kane et al., 2004; Redick et al., 2012). Two different forms of the Operation Span (i.e., different lists of words and equations presented in set orders) were presented in counterbalanced order at pre-training and post-training assessments.

3.2.2.2.3 Reading Span Task. The Reading Span is a computerized verbal measure of WM executive processes (Daneman & Carpenter, 1980; Unsworth et al., 2009). It has been shown to have strong internal consistency (α = .86–.88; Engle, Tuholski, et al., 1999; Kane et al., 2004; Redick et al., 2012) and test-retest reliability (α = .82; Redick et al., 2012; Unsworth et al., 2009). It has also been shown to converge with other measures of WM executive processes (r=.55–.73; Kane et al., 2004; Redick et al., 2012).

3.2.2.2.4 Symmetry Span Task. The Symmetry Span is a computerized visuospatial measure of WM executive processes (Kane et al., 2004). It has been shown to have strong internal consistency (α = .76–.81; Engle, Tuholski, et al., 1999; Kane et al., 2004; Redick et al., 2012) and test–retest reliability (α = .77; Redick et al., 2012; Unsworth et al., 2009). It has also been shown to converge with other complex span measures (r=.55–.71; Kane et al., 2004; Redick et al., 2012).

3.2.2.3 Reading. See Table 3.3 for a detailed description of each measure and the variables used from each measure for the analyses.

3.2.2.3.1 The Test of Reading Efficiency (TOWRE). The TOWRE is a measure of decoding; it measures a reader's efficiency and fluency of word reading, sight word recognition, and phonemic decoding (Torgesen et al., 1999). Participants were administered the Single Word Efficiency (TOWRE SWE) subtest and the Phonemic Decoding Efficiency (TOWRE PDE) subtest. Form A and Form B of the TOWRE were used in this study with different forms presented in counterbalanced order at pre-training and post-training assessments. The TOWRE (Torgesen et al., 1999) has been shown to have strong internal consistency (using alternate-form reliability for both subtests and total scores; α = .93–.96), two-week test–retest reliability (r=.82–.97), and inter-rater reliability (r=.99 across subtests and total score). It has also been demonstrated to have alternate form equivalence (*r* = .86 or higher for different age intervals) and to have high relationships between its subtests (r = .77 to .96). Torgesen et al. (1999) found that the TOWRE has also been found to have good concurrent validity with other measures of word attack skills and sight word reading (r=.86–.94).

3.2.2.3.2 The Nelson-Denny Reading Test – Reading Comprehension (NDRT-RC). The NDRT-RC (Brown et al., 1993) is a common measure of adult reading comprehension and reading rate including adults with a history of reading difficulties (Deacon et al., 2012; McGonnell et al., 2007; Parrila et al., 2007). Form G and Form H of the NDRT-RC were used in this study with different forms presented in counterbalanced order at pre-training and post-training assessments. It has been found to have high internal consistency (α=.92; Georgiou & Das, 2016) and adequate alternate-form reliability (r=.81; Brown et al., 1993). It is also positively correlated with verbal portions of aptitude tests (e.g., r=.71 with the College Board Scholastic Aptitude Test and r=.71 with the American College Testing Program; Wood, 1982).

3.2.2.4 Other Measures. To address another research question not included in this paper, participants were also administered the Self-Efficacy for Self-Regulated Learning Scale (Usher & Pajares, 2008) and the Academic Self-Efficacy questionnaire (Klassen et al., 2008). The data from these measures will not be reported here.

3.2.3 Training Task

Participants completed at-home training on a custom dual *n*-back working memory computer game called the N-IGMA. The program presented a series of visual and auditory stimuli simultaneously, and participants were instructed to make responses when the current auditory and/or visual stimulus matched the stimulus of the same sensory modality presented “n” items before. For instance, an “n” of two would mean that they needed to indicate if the current stimuli matched the stimuli from two trials back. Participants made no response on trials with no matches. After each response, participants were given visual feedback on whether their response was correct (i.e., a hit response) or incorrect (i.e., a false alarm response). After each of 20 blocks in a training session, participants were presented with their accuracy and average response time for the block. After participants completed five sessions, the stimuli and the number of trials per block were changed to maintain motivation and challenge. The time between presentation of the next stimuli pair (i.e., the interstimulus interval) was also changed in order to keep the approximate duration of each training session the same. The WM training group and the active control group received the same training program, but they were given different goals and the WM training group received an adaptive version whereas the active control group did not. Training task differences are described further below.

3.2.3.1 Working Memory Training Task. The WM training group received an adaptive version of the N-IGMA. They began at an *n*-level of one (i.e., matching to the last item seen or heard). Subsequent progression and regression of *n*-level occurred based on participants' accuracy performance. If their combined accuracy for auditory and visual stimuli for a block was greater than 90%, *n*-level increased by one. If combined accuracy was less than 70% on three consecutive blocks, the *n*-level was decreased by one. When there was a scheduled change to the stimuli and their presentations, participants began at an *n*-level of one to allow them to become familiar with and adjust to the changes. On all other training days, participants began at the same *n*-level they had ended at during their previous session. Participants were instructed to respond as accurately as possible with the goal of levelling up.

3.2.3.2 Active Control Group Training Task. The active control group received a non-adaptive version of the N-IGMA (i.e., fixed at an *n*-level of one). Participants were instructed to keep accuracy as high as possible while trying to improve their response speed (i.e., respond more quickly).

3.2.4 Procedures

3.2.4.1 Consent, Screening, and Background Characteristics. Participants came into the Cognitive Health and Recovery Lab testing space in the Life Sciences Centre at Dalhousie University and completed informed consent. Following informed consent, participants completed a self-report screening and background questionnaire (see Appendix G) to gather relevant demographic, academic, and health information, and to confirm eligibility for study participation.

3.2.4.2 Pre-Training Assessment. For the purposes of this study, participants were administered a pre-training assessment battery consisting of the LASSI-Conc subscale, the Item Memory and Location Memory subtests from the modified version of the DalCAB, the Operation Span, the Reading Span, the Symmetry Span, the TOWRE SWE, the TOWRE PDE, and the NDRT-RC. Assessment measures were administered in the same order, to all participants (see Appendix H for the test list). Since two versions of some of the measures were available, two test lists (i.e., Test List A and B) with the different versions of the measures were created and counterbalanced across groups. Within each training group, participants were randomly assigned to either Test List A or Test List B for the pre-training assessment in blocks of six with replacement. The assessor was blind to the participant training group assignment.

Computerized outcome measures were performed on an iMac®, 27-inch, 2.7 GHz Intel Core i5. Participants were centered, 19.75 inches from the screen. Responses were made with a two-button mouse (for the DalCAB and Reading Span), a computer keyboard (for the Operation Span and Symmetry Span), and/or a paper and pencil (for the Symmetry Span). Computer screen brightness was set to 50% and volume was set to the maximum volume. To limit computer screen glare during computerized test administration, a dim lamp was placed behind and to the left of the participant, out of sight, and the overhead lights were turned off.

3.2.4.3 Training Phase.

***3.2.4.3.1 Training Tutorial**.* Following the pre-training assessment, a second experimenter served as the trainer. Participants were informed that they would be completing one of two training tasks. The training tutorial for the assigned computer training task (i.e., either the WM training task or the active control task) was conducted on either the same computer as the computerized outcome measures or on the participant's personal laptop. The trainer guided participants through a 15 to 30-minute tutorial on how to access the training program from home and how to complete it.

Following the tutorial, each participant completed a Pre-Training Expectations Questionnaire asking them to indicate, on a 5-point Likert scale, how much they thought that the 3-week training activity would improve their performance on the assessment measures and other relevant abilities post-training (e.g., ability to concentrate while reading and use strategies to do well in school; Appendix M).

3.2.4.3.2 Training Period. Participants accessed the training activity website and completed training on their personal computers, outside of the laboratory. They were instructed to complete 10 training sessions over the course of three weeks, except for one participant who was instructed, prior to a change made to the study methodology, to complete 15 training sessions over the course of the 3-week period. They were informed that they could complete the training at any time of day and could only complete one training session a day.

Before beginning each session, participants rated their levels of alertness and motivation, and indicated the amount of sleep they had had within the past 24 hours (see Appendix N**)**. Each training session took approximately 30-40 minutes to complete without breaks. Once participants completed a training session, the program prevented them from completing another session until the following day. At the end of each training session, participants filled in a Computer Activity Log indicating the date, start time, and the duration of the session, reporting the results of the final block of the session, and recording any additional notes for the experimenter.

During the training phase, the trainer monitored participants' progress and were available, by e-mail, to answer any questions that the participants had. After participants completed five training sessions, the trainer e-mailed them to remind them of the changes to the training program and provided feedback on their performance (i.e., graphs of their performance across sessions and guidance on what they should focus on to improve performance in the remaining training sessions). The trainer also contacted participants to provide reminders about missed sessions and about their scheduled post-training assessment date.

3.2.4.4 Post-Training Assessment. Within one week following completion of the training period, participants returned to the laboratory. They completed the same assessment measures as in the pre-training assessment battery. The assessment was administered by the same experimenter as the one who administered the assessment battery prior to the training period. Following the post-training assessment, participants completed a Post-Training Expectations Questionnaire asking them to indicate, on a 5-point Likert scale, how much they thought that the 3-week training activity had improved their performance the measures given (see Appendix O). After exiting the study (either discontinuing participation or completion of the study), participants were debriefed and provided with either a combination of course credits and financial compensation, or financial compensation alone.

3.3 Results

Eight participants withdrew from the active control group (i.e., 36.4% attrition) and six participants withdrew from the WM training group (i.e., 30% attrition). Only three participants provided a reason for not completing the training program; they withdrew due to time constraints. Training data from withdrawn participants were excluded from analyses. Training data from one additional participant in the WM training group were excluded from the final analysis due to missing training data because of technical difficulties. Data from 14 participants in the active control group and 13 participants from the WM training group were retained for statistical analyses (see Figure 3-1 for the CONSORT flow chart for this study; see Table 3.1 for a summary of sample demographics).

3.3.1 Data Cleaning

All trials were included in the calculation of accuracy variables for the Location Memory and Item Memory tasks from the DalCAB. The data for each measure for each group (i.e., WM training and active control), were screened for extreme outliers using a cut-off of four standard deviations from the group mean. No extreme outliers were identified. In the WM training group, the data of one participant was incomplete for the LASSI-Conc and could not be included in the analyses. Data from two participants in the WM training group were excluded from the DalCAB Item Memory and Location Memory tasks; one because they were administered the incorrect version of the tasks and the other because of concern that they had confused the response keys for the task. In the active control group, one participant was not administered the Reading Span task due to technical difficulties. The means and standard deviations for each measure, following data exclusion, are presented in Table 3.4 for each training group at pre-training and post-training.

3.3.2 Is the HRD Training Sample any Different From HRD Students Who Did Not Complete Training?

We first evaluated whether our sample of trained HRD participants was likely representative of the broader undergraduate HRD population and thus making it appropriate to draw conclusions of the efficacy of this training program more broadly to that group. There were no differences between groups with regards to age, years of education, number of female-gendered individuals, ARHQ-R score, and anti-depressant/anti-anxiety medication usage (see Table 3.5 for a summary of demographics). We compared HRD participants who completed the training study ($n = 27$) to those who did not (those who participated only in Study 1; $n = 24$) on measures of self-reported attention to academic tasks, WM, and reading. Data from the Reading Span task could not be included in this analysis because it was not administered to participants in Study 1. We conducted Welch's independent samples t-tests (Delacre et al., 2017) for each test variable and computed the 95% confidence interval of Cohen's *d* (i.e., 95% $CI = d \pm 1.96 \sqrt{V_d}$) was computed after deriving the variance of Cohen's *d* using the following formula (Borenstein et al., 2009).

$$V_d = \frac{n_1 + n_2}{n_1 n_2} + \frac{d^2}{n_1 + n_2}$$

We then grouped variables from measures (with the exception of the LASSI-Conc) into factors. Variables from the DalCAB were grouped into factors of vigilance, orienting, executive control, and WM capacity based on conceptual relationships between variables (see Petersen & Posner, 2012) and their loadings in S. A. H. Jones et al. (2015) factor analysis (see Table 3.6). The Operation Span and Symmetry Span tasks, two WM executive measures of found to be highly correlated in the literature (e.g., Foster et al., 2015; Kane et al., 2004), were grouped into a WM executive factor. The variables from the TOWRE and NDRT-RC were grouped into a Reading factor. For each factor, a meta-analysis random effects model (Borenstein et al., 2009) was used to calculate an overall Cohen's *d* with 95% confidence intervals using the Cohen's *d* values and 95% confidence intervals from the Welch's t-tests. Effects sizes with 95% confidence intervals for each variable and weighted random factor were plotted on forest plots (see Figure 3-2). Significant effects are indicated by confidence intervals that do not cross zero. There were no significant differences at both the single variable and factor levels between HRD participants who completed the training study and those who did not.

3.3.3 Training Task Performance

Ten participants in the WM training group completed 10 sessions and one participant completed 9 sessions. The remaining two participants in the WM training group completed more than 10 sessions[1]; one completed 15 training sessions because they were instructed to do so prior to changes made to the study methodology, and the other completed 11 training sessions due to a technical error. For the latter participant, the final training session included the same stimuli, number of trials per block, and time between presentation of the next stimuli pair programmed for training sessions 6 to 10 (see Appendix L). The performance of the participant who completed 15 sessions declined following their 10th training session (i.e., slope of average n-level from sessions 1–10 was 0.09 and slope of average n-level from sessions 11–15 was -0.06) and the participant told the researcher that although they felt their motivation to complete the training sessions was good for the first 10 sessions, they felt it was low for the remaining sessions. For that reason, the slope of the daily average n-level achieved across that participant's first ten training sessions, rather than all 15, was used as a proxy for training improvement, and the average *n*-level achieved on their 10th training session was used as to represent their last day training performance.

Performance on the WM training task was considerably variable amongst participants (Figure 3-3). The maximum individual daily average *n*-level achieved across the training period ranged from 1.75 to 3.85. Average *n*-level on the first day ($M = 1.67$, $SD = 0.44$) was significantly lower than on the last day ($M = 2.26$, $SD = 0.86$), $t(13) = -2.94$, $p = .01$. Only five (i.e., ~39%) participants achieved a maximum daily average n-level equal to or greater than one level better than their average n-level achieved on the first day of training. The slope of the daily average n-level, which was used as a measure of training improvement, ranged from -0.14 to 0.17 with a mean of 0.05 ($SD = 0.09$). Improvement in n-level from first and last training sessions ranged from -0.8 to 1.8 with a mean average *n*-level increase of 0.6 levels ($SD = 0.7$). Average accuracy (%Correct) across ten training sessions (across nine training sessions for the one participant who did not complete ten) on the auditory stimulus task of the training program ($M(SD) = 76.5(4.7)$) was significantly greater than on the visual stimulus task ($M(SD) = 66.5(0.9)$), $t(12) = 7.8$, $p < .001$. Pairwise comparisons with Bonferroni adjustment for multiple

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[1] Removing these participants from the analyses had no substantive impact on the study results or conclusions drawn; therefore, we have presented the results with their data included.

comparisons were conducted between the first session of training and all subsequent training days for average accuracy on both stimulus tasks. Participants' accuracy on the auditory stimulus task was significantly greater on the first session of training than the seventh ($M_{\text{difference}} = -6.1$, $SE = 1.9$, $p < .05$), ninth ($M_{\text{difference}} = -6.0$, $SE = 1.9$, $p < .05$) and tenth sessions ($M_{\text{difference}} = -7.2$, $SE = 1.9$, $p < .01$) and no different from the other training sessions (*p*s > .06). Participants' accuracy on the visual stimulus task was no different on the first training session than any of the subsequent training sessions (*p*s > .26).

The participants in the active control group all completed the prescribed ten training sessions over the course of the 3-week period. Minimum daily average RTs for correct responses ranged from 437.6ms to 969.6ms (see Figure 3-4). The slope of daily average RT ranged from -37.7ms to 12.7ms. Reaction time on the first day (M = 810.6ms, SD = 147.1ms) was significantly slower than on the last day (M = 678.3ms, SD = 178.ms), $t(13) = 4.44$, $p = .001$. Maximum daily average accuracy ranged from 78.1% to 99.1% and the minimum ranged from 60.0% to 94.6% (see Figure 3-5). The slope of daily average accuracy ranged from -1.89% to .33%. Across participants, accuracy on the first day (M = 89.8%, $SD = 7.7$) was significantly higher than on the last day ($M = 86.0$, $SD = 8.7$), $t(13) = 2.96$, $p = .01$.

3.3.4 Research Question: Does Dual N-back WM Training Improve WM and Reading Performance in HRD University Students?

For a preliminary exploration of the impact of training, within-group changes on outcome measures were analyzed using paired-sample t-tests for the WM training group and active control group separately (see Table 3.4 for a summary of the results). In the WM training group, post-training performance was significantly better than pre-training performance for Operation Span total, $t(12) = -4.27$, $p = .001$, $d = -1.19$, 95% CI [-1.89, -.45]; and for Symmetry Span total, $t(12) = -4.19$, $p = .001$, $d = -1.16$, 95% CI [-1.86, -.44]. In the active control group, post-training performance was significantly better than pre-training performance for Operation Span total, $t(13) = -4.92$, $p < .001$, $d = -1.32$, 95% CI [-2.03, -.58]; for Symmetry Span total ($t(13) = -2.57$, $p = .02$, $d = -.69$, 95% CI [-1.26, -.09]; and for NDRT-RC - %Correct, $t(13) = -2.55$, $p = .02$, $d = -.69$, 95% CI [-1.26, -.09]. While these changes in outcome measures were seen in both groups, the relationship of these changes to WM training, specifically, was explored in further analyses as described below.

To evaluate the efficacy of dual *n*-back WM training in HRD university students compared to an active control training condition on the individual variables, regression analyses with an alpha-level of .05 and listwise deletion for missing data were conducted for each outcome variable with training group as the predictor, post-training performance as the outcome, and pre-training performance as a covariate. Participant performance was first standardized for each outcome variable by calculating z-scores relative to the grand mean on the same variable. This was done separately for the pre-training and post-training time points. The standardization procedure allowed for both an easier comparison of relative changes between the training groups as well as between tasks with different scales. Furthermore, because a high score on variables from the Item Memory and Location Memory tasks indicated worse performance, whereas higher scores on all other variables represented better performance, the variables from Item Memory and Location memory were multiplied by -1 so that high values always reflected better performance. As a result of the standardization process, the beta statistics generated from the regression were analogous to an adjusted mean difference and reflected an effect size (i.e., standard deviation difference between groups).

The results of the regression analyses for the individual variables are presented in Table 3.7 and Table 3.8. The model for self-reported attention on academic tasks (i.e., LASSI-Conc) was significant, indicating that 66% of the variance in post-training LASSI-Conc could be accounted for by the covariate and predictor variables, together. Looking at the unique contributions of covariate and predictor variables, pre-training performance positively predicted post-training performance, but training group was not a significant predictor of post-training performance. For the variables from the WM maintenance measures (i.e., Item Memory and Location Memory %Error from the DalCAB), the combination of the covariate and predictor variables did not predict a significant portion of variance in post-training performance. With respect to the variables from the WM executive measures (i.e., Operation Span, Symmetry Span, and Reading Span) all three models were significant; the portions of variance in post-training performance accounted for by the covariate and predictor variables combined were 55%

for the Operation Span model, 59% for the Symmetry Span model, and 30% for the Reading Span model. Looking at the unique contributions of covariate and predictor variables for all three models, pre-training performance was a significant pre-training performance positively predicted post-training performance, but training group was not a significant predictor of post-training performance. For the variables from the reading measures (i.e., TOWRE and NDRT-RC), the portions of variance in post-training performance accounted for by the covariate and predictor variables combined were 67% for both the TOWRE SWE and TWORE PDE models, and 46% for the NDRT-RC Reading Rate model. The combination of the covariate and predictor variables did not predict a significant portion of variance in post-training performance in the NDRT-RC - %Correct model. Looking at the unique contributions of covariate and predictor variables for all three models, pre-training performance was a significant pre-training performance positively predicted post-training performance, but training group was not a significant predictor of post-training performance. Forest plots were generated to aid in the visualization of training effects (see Figure 3-6 to Figure 3-7). Effect sizes (i.e., standard mean difference) with 95% confidence intervals for each individual variable were plotted (grouped by measures of WM maintenance, WM executive, reading, and self-reported attention on academic tasks). Significant effects indicated when confidence interval bars did not cross 0.

Following the regression analyses, we ran linear mixed models (LMM) for groupings of variables measuring the same constructs (i.e., WM maintenance, WM executive, and reading). The reason for doing so was to obtain estimated marginal means in order to more accurately evaluate whether training group was associated with more generalized cognitive ability changes. Shipstead et al. (2012) have argued that single tests scores reflect both the ability they are meant to measure, along with other systematic and random effects and therefore, evidence for training-induced post-training changes of a cognitive function cannot be definitive using single measures. The WM maintenance factor consisted of the percentage of errors made on the Item Memory and Location Memory DalCAB tasks; the WM executive factor consisted of the Operation Span Total, Symmetry Span Total, and the Reading Span Total; and the reading factor consisted of the TOWRE SWE and TOWRE PDE total items read correct correctly and the NDRT-RC - %Correct.

For all factors, we ran LMMs with training group entered as the predictor, pre-training entered as a covariate, and post-training performance as the outcome. For every factor, we ran multiple LMMs using maximum likelihood (ML) estimation to allow for the comparison of models of every variation of fixed and random effects and covariance structures offered in SPSS (IBM Knowledge Center, n.d.). Models were compared using the Bayesian Information Criterion (BIC); a BIC differences of 6 or greater indicated strong evidence for a better model (Raftery, 1995). Once the best model was identified, the final model was run with the Restricted Maximum Likelihood (REML) estimation as it is less biased than ML, especially with small sample sizes (McNeish & Stapleton, 2016).

For all factors, the most parsimonious model was one with fixed intercepts and fixed slopes. The estimated marginal means of each training group were used to generate adjusted marginal mean differences with 95% confidence intervals for each model and were used to generate a forest plot (see Figure 3-8). The adjusted marginal mean differences represent the magnitude of the difference between training groups on the post-training assessment while adjusting for performance on the pre-training assessment (i.e., covariate). A unit on the x-axis of the forest plots indicates one standard deviation and significant effects are indicated when confidence interval bars did not cross 0. There were no factor-level significant group effects.

3.3.5. Follow-Up Analyses

Having found no evidence of training effects in favour of the WM training condition, we conducted further exploratory analyses to explore possible reasons for our null findings.

3.3.5.1 Did WM Training Progress Affect Training Outcomes? To investigate whether performance on the WM training program was related to change in performance on outcome measures, bivariate correlations were conducted between the change in performance on the WM and reading outcome variables from pre-training to post-training (i.e., post-training performance–pre-training performance) and the WM training slope. WM training slope was significantly correlated with change in performance on Location

Memory %Error (r_9 = -.66, p = .02); a steeper WM training slope was associated with a greater reduction in percentage errors made on the Location Memory task from the pre-training assessment to the post-training assessment. WM training slope was not significantly correlated with pre- to post-training performance differences on Item Memory %Error (r_9 = -.23, p = .46), Operation Span Total (r_{11} = -.19, p = .53), Symmetry Span Total (r_{11} = -.25, p = .40), Reading Span Total (r_{11} = -.20, p = .51), TOWRE SWE (r_{11} = -.07, p = .82), TOWRE PDE (r_{11} = .11, p = .72), or NDRT-RC - %Correct (r_{11} = -.04, p = .91).

3.3.5.2. Did Initial WM Ability Affect WM Training Progress? To explore whether the participants' abilities to progress on the WM training program was impacted by their initial level of WM abilities, bivariate correlations were conducted between the WM training slope (i.e., slope of the average n-level achieved across the training period) and both the pre-training performance on the WM outcome variables and the average *n*-level achieved on the first day of training. WM training slope was significantly correlated with pre-training performance on Location Memory %Error (r_9 = -.58, p = .04); A steeper WM training slope was associated with a smaller percentage of errors made on the Location Memory task. WM training slope was not significantly correlated with pre-training performance on Item Memory %Error (r_9 = -.52, p = .07), Operation Span Total (r_{11} = .22, p = .46), Symmetry Span Total (r_{11} = .09, p = .77), Reading Span Total (r_{11} = .45, p = .12), and average *n*-level achieved on the first day of training (r_{11} = .11 p = .73).

3.3.5.3 Were There Differences in Group Motivation During the Training Period? We explored whether the WM training group and the active control group differed in their motivation to engage in the training activity over the course of the training period. To do this, we ran a LMM with REML estimation with training group (i.e., WM training and active control) and time (i.e., sessions one through to 10) as the predictors, and motivation ratings as the outcome. We followed the same procedures described earlier to identify the best fitting model and found that the most parsimonious model was one with fixed slopes and random intercepts. A two-tailed significance level was set at α = .05. There was a significant main effect of time, $F_{1,224}$ = 2.61, p < .01, but no significant effect of training group, $F_{1,25}$=2.51, p=.13, and no significant training group x time interaction, $F_{1,224}$ = .87, p = .55. Pairwise comparisons with Bonferroni adjustment for multiple comparisons of motivation ratings between the first session of training and all subsequent training days revealed that participants ratings of motivation were significantly higher on the first session of training than the eighth ($M_{\text{difference}}$ = 12.42, *SE* = 3.82, $p < .05$), ninth ($M_{\text{difference}}$ = 14.71, *SE* = 3.82, $p < .01$) and tenth sessions ($M_{\text{difference}}$ = 13.30, *SE* = 3.87, $p < .01$).

3.3.5.4 Were There Differences in Group Expectations for Training Effects? Lastly, we explored whether the WM training group and the active control group differed in their expectation (see Appendix M and Appendix O for the pre-training and post-training expectations questionnaires, respectively) of the impact that their training activity would have/had on their performance on the outcome measures, their concentration ability, their strategy use, and their confidence in certain abilities. First, composite scores were created by taking the average pre-training expectation ratings and average post-training expectation ratings for similar outcomes. Composites included expectations on different outcome measure types (i.e., WM maintenance, WM executive, Reading), their ability to concentrate while reading and during school activities, their use of strategies while reading and to do well in school. Their expectation rating of their confidence in their ability to understand class materials and to do well on academic tasks was not combined with other expectation ratings. See Table 3.9 for a summary of the categories of expectation ratings. We then ran LMMs with REML estimation with training group (i.e., WM training and active control) and time (i.e., pre-training and post-training) as the predictors, and expectation rating categories as the outcomes. We followed the same procedures described earlier to identify the best fitting models and found that for all expectation rating categories, the most parsimonious model was one with fixed intercepts and fixed slopes. A two-tailed significance level was set at $\alpha = .05$.

For most of the expectation categories, there were no significant main effects of time or of training group, and no interaction between time and training group. The only exception to this was participants' expectation ratings for their performance on WM maintenance measures (i.e., WM maintenance expectations category) and for their ability to concentrate while reading and during school activities (i.e., Concentration expectations category). For the WM maintenance expectations category, there was no significant main effect of time, $F_{1,41} = 2.42$, $p = .13$, or interaction between time and group, $F_{1,41} = .33$, $p =$

.57; however, there was a significant main effect of group, $F_{1,41} = 4.54$, $p < .05$. Participants in the WM training group rated their belief that their assigned training activity would/did improve their performance on the WM maintenance measures higher than the active control group ($M_{\text{difference}} = .39$, $SE = .19$). For Concentration expectations category, there was no significant main effect of group, $F_{1,50} = .08$, $p = .78$, or interaction between time and group, $F_{1,50} = .73$, $p = .40$; however, there was a significant main effect of time, $F_{1,50} = 5.42$, $p < .05$. Participants rated their expectation at pre-training as significantly higher than their expectation at post-training ($M_{\text{difference}} = .39$, $SE = .17$).

3.4 Discussion

The current study's aim was to evaluate the potential of computerized WM training as an intervention to support this HRD students. We examined whether WM training using a dual *n*-back task resulted in improvements in HRD students' WM and reading performance compared to an active control group. To our knowledge, this study is the first study to investigate the effectiveness of training on a WM executive task in an undergraduate sample of young adults with weaknesses in reading.

We found no evidence for WM training-related near transfer to untrained WM measures, or far transfer to decoding and reading comprehension measures. After accounting for pre-training performance, the WM training and the active control groups performed similarly at post-training on WM maintenance, WM executive, decoding, and reading comprehension measures following training. These findings are contrary to previous meta-analytic findings suggesting that WM training can result in small to large improvements on untrained WM tasks (Melby-Lervåg et al., 2016; Schwaighofer et al., 2015; Soveri et al., 2017) and to significant, albeit small, transfer to abilities associated with WM (Au et al., 2015; Melby-Lervåg & Hulme, 2013; Soveri et al., 2017). The results are in keeping with our hypothesis that WM training would not transfer to decoding but provide evidence against our hypotheses that it would result in near transfer to untrained WM tasks and far transfer to reading comprehension of passages.

A weaker signal for learning on the WM training task was observed in our sample of HRD students than in other studies using dual *n*-back training programs. WM training task performance was highly variable amongst participants. Although HRD participants in the WM training group made significant training gains on the training task, the gains were smaller than those observed in previous adaptive dual *n*-back training studies with healthy young adults not specifically selected for learning or cognitive difficulties (e.g., Jaeggi et al., 2010; Küper & Karbach, 2016; Redick et al., 2013; Rhodes & Katz, 2017; Salminen et al., 2012). The WM training group in our study averaged 0.6 *n*-levels of improvement (i.e., mean *n* first session = 1.7; mean *n* last session 2.3). In contrast, young adults in other studies have shown gains of approximately 1.5 to two *n*-levels following 10 sessions of dual *n*-back training programs with similar adaptive features (i.e., level-up and level-down criteria) as those used in the present study (Jaeggi et al., 2010; Redick et al., 2013; Rhodes & Katz, 2017). HRD students' lower gains on the dual *n*-back training task could indicate that, for whatever reason, participants in our study did not learn enough from practicing on the training task to generalize to other WM tasks or to tasks of related functions.

Participant motivation, engagement, and effort in the training task could have negatively impacted participants' performance on the training task. In the present study, we asked participants to rate their level of motivation to engage in the training task before beginning each training session. We found that participants' average ratings of motivation significantly declined from the first day to the later training. There was no difference in the rate at which participants' reported motivation levels declined in the WM training group and the active control group. Research investigating the role of motivation in predicting training performance and transfer has been limited and results have not been consistent. A few studies have found positive associations between motivation and training performance. For instance, Brose et al. (2012) found that in a non-clinical sample of young adults, daily ratings of their motivation to engage in a 3-back WM training task was positively related to daily performance on that task. Similarly, Maraver et al. (2016) found that young adults' combined motivation ratings of their involvement in the WM training program, their perceived difficulty of the program, their perceived challenge of improving over levels of the program, and their expectations for their achievement, were positively associated with training slope. Higher motivation ratings were also associated with greater transfer to the Operation Span task. In contrast, Guye et al. (2017) found no relationships between rating of training performance motivation averaged across the training period and training performance slope.

Unfortunately, we did not directly ask participants about their levels of engagement and effort in the training, therefore, we can only speculate that the observed decline in motivation of the participants in our study may have been accompanied by a decline in engagement or effort, interfering with the potential effectiveness of the training program. Notably, however, although participant accuracy on the verbal stimulus task of the adaptive dual *n*-back training task was lower on later training sessions than on the first training day, they maintained a mean accuracy greater than 70%. This level of maintained accuracy was achieved, despite an average increase in *n*-level (i.e., increase in task difficulty). Further, there were no differences between the WM training and active control group's expectations of the impact of training before and after training. Thus, although declining motivation might have had a negative impact on participants' performance on the training task, it is likely that other barriers to progress on the training task were present.

Another potential contributor to participant performance on the training task and transfer is the fit between task difficulty and participant baseline ability. According to Lövdén et al.'s (2010) supply-demand mismatch model, to enact change in a person's cognitive system, the environmental demands must be greater than the demands the cognitive system is comfortable handling but must not exceed a level that the system cannot manage and adapt to. The dual *n*-back training task used in this study may have been inappropriately challenging for HRD students who have shown relative weaknesses in WM in both verbal and visuospatial domains (Study 1). HRD student's initial performance on the training task gives some indication of this. Due to the absence of reported training performance means and standard deviations in other studies with young adults, direct statistical comparison between our sample and others was not possible; however, baseline training task performance of HRD students in our sample (i.e., mean *n*-level of 1.7) was numerically lower than those reported previously in healthy young adult samples (i.e., mean *n*-level typically ranging between 2 and 2.5; Jaeggi et al., 2010; Küper & Karbach, 2016; Redick et al., 2013; Rhodes & Katz, 2017). The visual stimulus task on the dual *n*-back task may have been the key component preventing participants from progressing on the training task. In support of this, we found that participants in the WM training group were more accurate on the auditory stimulus task of the dual *n*-back training program than the visual stimulus task, and that accuracy on the visual stimulus task did not improve over the course of training. Thus, it appears that the visual stimulus task more greatly limited participants' abilities to level up to higher *n*-levels and to prevent levelling down. The added complexity of using a dual *n*-back task rather than a single *n*-back tasks may have been too demanding for participants' cognitive systems to manage and effectively adapt to for the visual stimulus task. In that case, progression on the auditory stimulus task to challenging enough levels would have been hindered, providing limited pressure on participants' cognitive systems to increase WM capacity and/or enhance cognitive efficiency. Comparable transfer effects have been found following training on single and dual *n*-back tasks (e.g., Jaeggi et al., 2010, 2014; for meta-analyses see Au et al., 2015; Soveri et al., 2017), thus, given our findings, training on single *n*-back tasks rather than on a dual *n*-back task might be a more appropriate avenue for training WM in HRD university students.

The HRD students' baseline cognitive abilities may have also had an impact on their potential to learn from and improve on the dual *n*-back task. Studies outside of the cognitive training literature have found that WM is important for explicit learning, whereby stronger WM abilities have been associated with better learning (e.g., Shute, 1991; Unsworth & Engle, 2005). Initial performance on the training task in our study was not associated with training slope, consistent with findings from previous studies with participants in late adolescents (Ørskov et al., 2021) and young adults (Rhodes & Katz, 2017). We did, however, find that baseline performance on a visuospatial WM maintenance task was significantly associated with training slope, with better baseline performance associated with greater gains on the training task. Based on guidelines proposed by Cohen (1992; i.e., $r = |.1|, |.3|, |.5|$ for small, medium, and large effects respectively), the size of this effect was large. Although associations between training slope and baseline performance on a verbal WM maintenance and on a verbal WM executive task were found to be large and medium in magnitude, respectively, they did not achieve significance. Failure for medium to large effects to meet criteria for significance could be consequent to the confounding influence of our small sample size on *p* values (Sullivan & Feinn, 2012). Nevertheless, the finding that baseline performance on at least one measure of WM is in keeping with several recent studies that found that individuals with lower baseline pre-training cognitive abilities progress less on WM training tasks (Foster et al., 2017; Ørskov et al., 2021; Wiemers et al., 2019). For example, Wiemers et al. (2019) analyzed a combined dataset of seven studies wherein a total of 192 young adults (i.e., 18 to 30 years) completed 10-20 sessions of training on complex span task(s). The authors found that pre-training fluid intelligence, as well as WM performance on complex span and running-memory span tasks, were positively associated with training slope. Similarly, Ørskov et al. (2021) analyzed the data of 217 Danish students ($M_{\text{Age}}(SD)$ = 17.55(1.46) years) who completed nine sessions of adaptive dual *n*-back training. The authors found that pre-training performance on measures of visual and verbal short-term memory, and of fluid intelligence were positively associated with training slopes on the training task; they did not administer WM executive measures. HRD students' weaknesses in attention and WM relative to their NRD peers (Study 1), may have restricted their learning capacities and rates of progress on the dual *n*-back training task used in this study.

Due to the limited gains that HRD participants made on the training task, it is not surprising that transfer to untrained tasks was not observed. Some researchers have found that training task performance is linked to training effects. For instance, Bürki et al. (2014) found that healthy adults aged 18 to 38 years and over 60 years of age who improved more over 10 sessions of adaptive verbal single *n*-back training showed greater improvements on a numerical WM updating task, a measure of fluid intelligence, and a simple reaction time task, after controlling for the effects of age-group and fluid intelligence. Further, specific to transfer to reading comprehension outcomes, Chein and Morrison (2010) found evidence of significant transfer to reading comprehension subtest from the Nelson-Denny Reading Test only in a subset of their undergraduate participants who showed improved performance over 20 sessions on the visuospatial complex span training task. Although we did not find that training task performance in our sample of HRD university students was associated with transfer to the Nelson-Denny Reading Test, we did find that participants with greater gains on the WM training task demonstrated greater gains on one of the near transfer tasks (i.e., the visuospatial WM maintenance). These findings provide some support for the link between training performance and transfer in our sample of HRD students. In contrast to findings from individual studies, Au et al. (2015) conducted a meta-analytical review of *n*-back WM training in healthy adults aged 18 to 50 years. The authors found no evidence for training slope as a predictor of post-training effect size (i.e., standard mean differences between training and control groups) while controlling for baseline differences. Notably, however, the authors categorized training slopes three median absolute deviations of 0.07 away from the overall median of 0.65 as outliers; thus, studies with very small training slopes were not represented in their analyses. The mean training slope (i.e., 0.05) and maximum training slope (i.e., 0.17) observed in the current study were well below Au et al.'s overall median slope (i.e., 8.6 and 6.9 median absolute deviations below, respectively), and would have been excluded from their meta-analysis as extreme outliers. It thus remains possible that a minimum degree of improvement on *n*-back training tasks may be necessary for transfer to occur, a criterion likely unmet in the current study; however, once minimum gains on the training task are achieved, training slope may no longer moderate transfer effects.

Given the weak signal for learning on WM training task, little can be said at this time regarding the use of *n*-back training for the purpose of improving HRD reading performance; however, HRD students' performance on the training task and their interest in participating in the study provide information regarding their abilities and the feasibility of time-demanding interventions. The specific dual *n*-back training task and procedure used in this study may have been an inappropriate intervention for improving the WM and reading skills of HRD students. Our findings suggest that these students' WM skills may be too weak to effectively learn and progress sufficiently on the training task. This is especially notable and informative regarding HRD students' learning difficulties given that samples from other populations commonly presenting with cognitive weaknesses, such as stroke patients (e.g., Ploughman et al., 2019) and adults with ADHD (e.g., Salmi et al., 2020), have been successful in training on similar dual *n*-back tasks. Further, it was challenging to recruit and retain HRD participants in the current study when the training protocol was set to 15 sessions; consequently, we decided to reduce the number of training sessions to 10. Whereas in other studies using dual *n*-back training programs researchers have had participants agree to and comply to as many as 20 to 25 training sessions (Jaeggi et al., 2010; Lawlor-Savage & Goghari, 2016; Matysiak et al., 2019), interventions for HRD students may need to have more limited time requirements. Although the current study failed to identify an effective and feasible WM training program for HRD students, it provided us with greater insight into what training program characteristics would be most suitable for HRD students and their baseline abilities.

It is also important to consider the possibility that, even if participant factors (e.g., motivation, baseline cognitive abilities, etc.) had been favourable for learning on the dual *n*-back training task used in this study, training may have still failed to improve HRD students' reading performance. According to the capacity-efficiency model, transfer of training gains to other untrained activities occurs consequent to increases in WM capacity and/or enhanced WM efficiency. Although gains in WM capacity should result in broad transfer to related tasks, transfer from enhanced WM efficiency may be much narrower. With increased WM efficiency, transfer is expected to occur only when acquired knowledge, strategies, or automatization of basic processes or novel cognitive routines can be effectively applied to other activities (Gathercole et al., 2006; von Bastian et al., in press; von Bastian & Oberauer, 2014). Although previous research has found evidence in favour of near and far transfer following training on *n*-back tasks, the most robust evidence for transfer has been to untrained *n*-back tasks and far-transfer effects, when observed, are typically small (Au et al., 2015; Soveri et al., 2017). Rather than improving WM capacity, training on *n*-back tasks may lead to task-specific strategy development or improvements in attention and processing speed that have only limited impact on other tasks. In the current study, failure to observe near transfer to untrained WM tasks suggests that training on the dual *n*-back task did not expand HRD students' WM capacities. Further, failure to observe near and far transfer to any outcomes suggests that if any strategies were generated, or if any basic cognitive processes or novel cognitive routines were automatized through training, they were not applicable or effectively applied to the outcome activities. Given the potential impact of intervention-specific and participant-specific factors on training performance and transfer discussed earlier, we cannot draw strong conclusions from our data regarding the potential for WM training to be effective in improving HRD students' WM and reading skills. It is clear, however, that a greater understanding of the mechanisms of transfer is needed for the purposes of understanding which training approaches are most likely to improve skills or abilities of interest, such as reading comprehension, and for whom.

3.4.1 Limitations and Future Directions

A critical limitation of this study is that it was significantly underpowered. The original target sample size for this study was twenty-one participants in each group (i.e., total sample of 42), similar to other studies that have found significant near and far transfer effects on WM (e.g., Chein & Morrison, 2010) and reading outcomes (e.g., Chooi & Logie, 2020; Clouter, 2013). Due to recruitment challenges, participant attrition, and early termination of data collection due to COVID-19 research restrictions, the targeted sample size was not met; the final sample consisted of 13 participants in the WM training group and 14 participants in the active control group. Based on estimates of small near transfer effects of *n*-back training to non-*n*-back untrained WM outcomes (i.e., $g = 0.18$; Soveri et al., 2017), a post-hoc power analysis using G*Power 3.1 (Faul et al., 2009) revealed that the present study had less than a 8% chance of finding true WM training effects. Underpowered studies are a common issue in the WM training literature that should be addressed in future studies (Melby-Lervåg et al., 2016).

Further, the number of participants that withdrew from the study following randomization reflected a high attrition rate (36.4% from the WM training group and 30% from the active control group). Participant dropout could have been due to several factors, including but not limited to the tolerability of the training task (e.g., difficulty, boredom, etc.), motivational factors, time commitment of training during the academic term, and personality characteristics. Post-hoc analyses revealed no differences in baseline WM and reading performance, ARHQ-R scores, or participant demographics (i.e., age, years of education, gender) between participants who remained in the study and those who dropped out. Most of the participants who discontinued training did not provided a rationale; however, three participants cited time constraints as their reason for dropping out. Although the minimum number of training sessions that are needed for transfer to occur is not known, meta-analytical reviews of *n*-back training in non-clinical samples have failed to identify the number of training sessions as moderator training effects (Au et al., 2015; Soveri et al., 2017). Further, shorter training sessions may be associated with greater training effects (Au et al., 2015) and lead to greater training adherence. Identifying the optimal dose of *n*-back training for adherence and efficacy in HRD students will be an important topic for further research. Future studies could also explore other ways of promoting participant buy-in and training adherence such the inclusion of psychoeducation regarding the WM and reading skills of HRD students and how WM contributes to reading performance.

Whereas the current study used multiple measures of WM with stimuli from different domains (i.e., visuospatial and verbal), it included only one measure of reading comprehension. In addition to variance from the construct of interest, scores on individual complex tasks are impacted by other influences such as measurement error and task-specific sources of variance (see Schmiedek et al., 2014 for a discussion on this issue with measures of WM). Measures of reading comprehension are process-impure and are not equivalent. Differences in the processing demands of different reading comprehension measures have been found (Andreassen & Bråten, 2009; Cutting & Scarborough, 2006; Keenan et al., 2008; Kendeou et al., 2012). Further research may address this issue by using multiple measures of reading comprehension and a latent variable approach (Shipstead et al., 2012).

Future studies may also explore combining WM training with other interventions to enhance learning from training. Performance on cognitive tasks, including *n*-back tasks, has been found to be significantly impacted by strategy use (Assecondi et al., 2021; Fellman et al., 2020; Laine et al., 2018). Individuals with low WM abilities, however, may not have the resources available to generate, implement, and/or adapt their strategies effectively to enhance performance on cognitive tasks (Lövdén et al., 2010) and may benefit from other tools to enhance their cognitive resources while training. A recent study by Assecondi et al. (2021) investigated the effects of combining two sessions of training on an adaptive spatial *n*-back task with strategy instruction and non-invasive direct current stimulation (tDSC). The authors found that in adults aged 18 to 29 years with weaker baseline WM abilities significantly improved on the trained task only when training was combined with both strategy instruction and tDSC; they did not show significant gains following training alone or training combined with either strategy instruction or stimulation alone. Given these findings and HRD students' weaknesses in WM relative to their NRD peers (Study 1), WM training combined with strategy instruction and tools to enhance plasticity, such as tDSC, may be more beneficial for this group than training alone.

3.4.2 Conclusions

The current study found no evidence of near transfer effects of dual *n*-back training to untrained WM maintenance and WM executive measures, nor far transfer effects to decoding and reading comprehension in university students with a history of reading difficulties (HRD). Although the results failed to reject the null hypothesis regarding the effectiveness of WM training in improving WM functioning and related functions in HRD students, strong conclusions cannot be drawn due to the small sample size of this study and the weak signal for learning on training task. Difficulties with participant recruitment and high attrition rates, also raise concerns regarding the feasibility of training program used in this study as an appropriate intervention for HRD students. It remains, however, that HRD students, relative to their NRD peers, have weaknesses in both WM and reading, and links between their WM and reading abilities have been identified (Study 1). Further investigation into the potential benefits of computerized WM training to HRD students' reading skills and identifying interventions that are feasible and suitable for those students is warranted.

Table 3.1

Demographic information of WM training group and active control group participants

	WM Training Group (n=13)	Active Control Group (n=14)	Group Comparisons
Age (years)	20.31 (2.14)	19.00 (1.41)	$p = .08$ [a]
Education (years)	13.62 (1.39)	13.14 (1.23)	$p = .36$ [a]
# of Females	9	9	$p = .79$ [b]
ARHQ-R Score	16.23 (3.47)	16.98 (4.31)	$p = .65$ [a]
Number Using Anti-Depressant/Anxiety Medication	1	1	$p = .16$ [b]
Number Using Stimulant Medication	2	1	$p = .96$ [b]

Note: Standard deviation in brackets; a- Welch’s independent samples t-test; b- chi square test

Table 3.2

Descriptions of WM Measures and the Variables Used from Each Measure

Measure	Description	Variables Used for Analyses
The Learning and Studying Strategies Inventory: Concentration Subscale (LASSI-Conc; Weinstein, 2002)	The LASSI is a 10-scale self-report measure that evaluates how aware a student is about learning and study strategies and their use of them. The LASSI-Conc subscale consists of 8-items that reflect a respondent's self-rated ability to direct and maintain their attention on academic tasks. Participants rated how well each statement describes them on a 5-point Likert scale. Ratings range from (a) – *not at all typical of me to* (e) – *very much typical of me*. Total raw scores can range from 8 to 40 with higher scores indicating more effective use of their concentration skills.	Total raw score
Dalhousie Computerized Attention Battery (DalCAB) – modified version	A battery of eight computerized tasks designed to measure different attention networks (i.e., vigilance/alerting, orienting, and executive control; (Fan et al., 2002, 2005; Fernandez-Duque & Posner, 2001; Petersen & Posner, 2012). Reaction time and accuracy are recorded for each task. The tasks are described in detail in S. A. H. Jones et al. (2015) and include: Simple Reaction Time (SRT), Go/No-Go (GNG); Choice Reaction Time (CRT), Dual Task (DT); Vertical Flanker; Item Memory (IM), Location Memory (LM), and Visual Search (see Appendix K for a description of each task). The modified version of the DalCAB consists of 50% fewer trials for each subtest.	Two variables from the modified version of the DalCAB were used for this research project as measures of working memory (WM) maintenance: percentage of errors across set sizes on the Item Memory task (IM-%Error) and on the Location Memory task (LM-%Error)

Measure	Description	Variables Used for Analyses
Operation span task (Engle, Kane, et al., 1999; modified from Kane et al., 2004)	A computerized verbal WM executive task (Kane & Engle, 2003), specifically a complex span task, that requires participants to study unrelated words for later recall alternating with an arithmetic task. Participants are presented with a math equation (e.g., “is (7x2)-1=14?”) and must read the equation out loud, say “yes” or “no” if the equation is correct, and press the corresponding “y” or “n” key on the keyboard. Fifty percent of the equations are correct. They are then presented with a word in the centre the screen for 1000ms that they must read out loud and try to remember. Following a 500ms delay, participants are presented with another equation question and word to remember, or a recall instruction. When presented with a recall instruction, participants must recall out loud all the words that they were presented in the block, in the order that they were presented, while the assessor records them. Each block of trials consisted of recall set sizes of 2, 3, 4, or 5 words. Participants practice the task twice at a set size of three. A total of 42 experimental trials are given across 12 blocks with three blocks of each set size presented in pseudorandom order.	The total number of words correctly recalled in the correct order position, summed across set sizes
Symmetry span task	A computerized visuospatial WM executive task (Kane et al., 2004), specifically a complex span task, that requires participants to remember the order of a series of red square locations in a matrix, alternating with making symmetry judgments. Participants are presented with an 8x8 matrix with black and white squares in the centre of the screen and must determine whether the filled black squares in the matrix were symmetrical across its vertical axis. They press the “y” key on the keyboard to indicate if the matrix is symmetrical or press the “n” key if it is not. Fifty percent of the matrices are symmetrical. Following their response and a 500ms delay, participants are presented with a 4x4 square matrix at the centre of the screen for 1000ms with one single red square. They must remember the location of the red square. Following a 500ms delay, participants are presented with another symmetry judgment trial and 4x4 matrix, or a recall instruction. When presented with a recall instruction, participants must recall the location of the read squares that they were presented in the block in the order that they were presented by marking them on answer sheets. Each block of trials consisted of two to five symmetry judgments and	The total number of red square locations correctly recalled in the correct order position, summed across set sizes

Measure	Description	Variables Used for Analyses
(Continued) Symmetry span task	4x4 matrices with a red square (i.e., set sizes 2, 3, 4, or 5). Participants practice the task twice at a set size of three. A total of 42 experimental trials are presented across 12 blocks; three blocks of each set size presented in pseudorandom order.	
Reading span task	The Reading span is a computerized verbal WM executive task (Daneman & Carpenter, 1980), specifically a complex span task, that requires participants to remember unrelated letters (F, H, J, K, L, N, P, Q, R, S, T, Y) while reading sentences and judging whether or not they made sense (Unsworth et al., 2009). Participants are presented with a sentence on the computer screen (e.g. ‘‘The prosecutor’s dish was lost because it was not based on fact.”) and they must indicate whether the sentence makes sense or not. Each sentence includes 10-15 words and nonsense sentences were created by taking a normal sentence and changing one word (e.g., “dish” from “case”). A time limit for sentence reading is calculated for each participant based on their average length of time taken to read sentences on earlier practice trials (i.e., mean time plus 2.5 standard deviations). If a participant exceeds this time limit, the program proceeds to the next task in sequence and counts the sentence trial as an error. Following sentence judgment, a letter appears on the screen for 1000ms that the participant must try to remember. They are then presented with another sentence judgment and a letter to remember or a letter recall screen. When presented the letter recall screen, participants click on the letters that they were presented in the block, in the order that they were presented, from a 4x3 matrix of letters. Each block of trials consisted of set-sizes of 3, 4, 5, 6, or 7. Before beginning the experimental trials, participants practice the sentence judgment task, the letter memory task, as well as the dual task (both tasks together). A total of 75 letters and 75 sentence judgment problems (approximately ½ made sense) are presented across 15 blocks; three blocks of each set size are presented in randomized order for each participant.	Total number of letters selected in the correct order position, across set sizes

Table 3.3

Descriptions of Reading Measures and the Variables Used from Each Measure

Measure	Description	Variables Used for Analyses
The Test of Reading Efficiency (TOWRE; Torgesen et al., 1999)	Single Word Efficiency (TOWRE-SWE) subtest: a measure of single word reading efficiency. Participants are presented with a list of 104 real words on a paper and they are asked to read as many items as they can in 45 seconds.	Total number of correctly pronounced items
	Phonemic Decoding Efficiency (TOWRE-PDE) subtest: a measure of phonemic decoding efficiency. Participants are presented with a list of 63 phonemically regular non-words on a paper and they are asked to read as many items as they can in 45 seconds.	Total number of correctly pronounced items
The Nelson-Denny Reading Test – Reading Comprehension (NDRT-RC; Brown et al., 1993)	A paper-and-pencil measure of reading comprehension and reading rate. Participants are given 20 minutes to read five short passages at a normal reading rate and respond to 38 factual and inferential multiple-choice questions about the passages. For reading rate, participants indicate what line of the first passage they have read to after the assessor notified them that a minute had passed.	Reading comprehension: Percent of correct answers (untimed reading comprehension; Deacon et al., 2006, 2012). This variable is calculated dividing the number of correctly answered questions by the number of attempted questions Reading rate: Number that corresponds to the last sentence they were reading at one minute (i.e., larger number means further in text)

Table 3.4

Pre-training and Post-training Performance on Assessment Measures By Training Group

Variable	WM Training Group (n=13)					Active Control Group (n=14)				
	Pre-Training		*Post-Training*		*Pre/Post Comparison*[c]	*Pre-Training*		*Post-Training*		*Pre/Post Comparison*[c]
	M	*SD*	*M*	*SD*	*p*	*M*	*SD*	*M*	*SD*	*p*
LASSI-Conc	24.3[b]	5.0	24.4[b]	4.1	.847	25.6	5.5	26.3	5.6	.496
Item Memory %Error	16.1[c]	5.1	17.3[c]	10.1	.751	16.9	9.6	15.5	8.9	.659
Location Memory %Error	22.1[c]	3.1	16.1[c]	8.7	.072	18.1	5.5	17.6	9.5	.873
Operation Span Total	22.3	5.5	27.6	4.5	**.001**	25.6	5.8	30.3	5.3	**<.001**
Symmetry Span Total	19.5	7.6	25.5	7.8	**.001**	25.1	6.3	28.3	6.3	**.023**
Reading Span Total	42.0	10.4	45.6	14.5	.374	51.9[c]	8.4	53.8[d]	9.1	.412
TOWRE SWE	88.5	8.3	89.2	5.9	.714	91.6	9.6	91.4	9.8	.736
TOWRE PDE	45.9	8.0	45.4	10.6	.773	46.1	11.7	48.6	9.9	.135
NDRT-RC – Reading Rate	245.7	73.9	249.8	56.1	.846	284.2	106.3	279.9	103.0	.824
NDRT-RC – % Correct	77.1	13.6	83.6	4.5	.094	80.8	10.0	87.0	7.3	**.024**

Note: a- paired samples t-test; b- data from 12 participants; c- data from 11 participants; d- data from 13 participants; M=Mean; SD=Standard Deviation; RT=Reaction Time

Table 3.5

Demographic information of HRD participants who completed the training study (i.e., Trained) and those who did not (i.e., Untrained)

	Trained (n=27)	Untrained from Study 1 (n=24)	Group Comparison
Age	19.63 (1.88)	19.71 (1.57)	$p = .87^{a}$
Education (years)	13.37 (1.31)	13.33 (1.27)	$p = .92^{a}$
# of Females	18	18	$p = .51^{b}$
ARHQ-R Score	16.15 (4.95)	17.42 (5.76)	$p = .40^{a}$
Number Using Anti-Depressant/Anxiety Medication	2	1	$p = .62^{b}$
Number Using Stimulant Medication	3	1	$p = .36^{b}$

Note: Standard deviation in brackets; a- Welch’s independent samples t-test; b- chi squared test

Table 3.6

Description of DalCAB Variables from Study 1 used in Study 2 Follow-up Analyses

Factor	Variable	Description
Vigilance	SRT – Reaction Time (RT)	▪ Mean RT across all trials
	SRT Preparation Effect - RT	▪ (RSI 500ms RT – RSI 1500ms RT)
	CRT - RT	▪ Mean RT across all trials
	Feature Search (FeatS) - RT	▪ Mean RT on feature search trials averaged across set sizes
Orienting	Conjunction Search (ConjS) - RT	▪ Mean RT on conjunction search trials averaged across set sizes
	ConjS – RT Slope	▪ Slope of RT smallest set size to largest set size on conjunction search trials
Attentional Control: Switching/ Shifting	DT Switch Cost - RT	▪ (Switch trials RT – No switch) trials RT on the choice reaction time task during the DT subtest
	DT Cost - RT	▪ (CRT task during the DT subtest RT - CRT subtest RT)
Attentional Control: Interference Control/ Conflict Resolution	Flanker Interference (Flanker Int) - RT	▪ (Incongruent trials RT – Congruent trials RT)
	Flanker Int - %Error	▪ (Incongruent trials %Error – Congruent trials %Error)
Attentional Control: Response Inhibition	GNG – 20% Go - %False Alarms (FA)	▪ Percentage of false alarms on 20% go frequency trials
	GNG – 80% Go - %FA	▪ Percentage of false alarms on 80% go frequency trials
Working Memory Maintenance	Item Memory %Error	▪ Percentage of errors averaged across set sizes
	Location Memory %Error	▪ Percentage of errors averaged across set sizes

Table 3.7

Regression Results for Self-Reported Attention on Academic Tasks, WM Maintenance, and WM Executive, with Training Group as the Predictor, Pre-Training Performance as a Covariate, and Post-Training Performance as the Outcome

Outcome	Predictor Variable	*B* (SE)	95% CI *B*	*t*	Fit
LASSI-Conc Post-Training	(Intercept)	-0.01 (0.12)	-0.25, 0.24	-.05	
	LASSI-Conc[a] Pre-Training	0.8 (0.12)	0.55, 1.05	6.57***	
	Training Group	-0.08 (0.12)	-0.33, 0.17	-.68	
					R^2=0.66***
Item Memory (IM) %Error Post-Training	(Intercept)	-0.01 (0.21)	-0.45, 0.42	-.06	
	IM %Error Pre-Training	0.50 (0.21)	-0.39, 0.49	.23	
	Training Group	-0.10 (0.21)	-0.53, 0.34	-.47	
					R^2=0.01
Location Memory (LM) %Error Post-Training	(Intercept)	0.01 (0.21)	-0.43, 0.44	.03	
	LM %Error Pre-Training	-0.08 (0.23)	-0.56, 0.40	-.35	
	Training Group	0.05 (0.23)	-0.42, 0.53	.24	
					R^2=0.01
Operation Span (OSpan) Total Post-Training	(Intercept)	0 (0.14)	-0.28, 0.28	-.02	
	OSpan Total Pre-Training	0.72 (0.14)	0.43, 1.02	5.03***	
	Training Group	-0.06 (0.14)	-0.35, 0.23	-.44	
					R^2=0.55***
Symmetry Span (SymSpan) Total Post-Training	(Intercept)	0 (0.13)	-0.26, 0.27	.03	
	SymSpan Total Pre-Training	0.8 (0.14)	0.51, 1.09	5.70***	
	Training Group	0.1 (0.14)	-0.19, 0.39	.73	
					R^2=0.59***
Reading Span Total Post-Training	(Intercept)	0 (0.17)	-0.35, 0.35	.00	
	Reading Span Total Pre-Training[a]	0.5 (0.2)	0.09, 0.91	2.50*	
	Training Group	-0.09 (0.2)	-0.5, 0.31	-.47	
					R^2=0.30*

Note: WM=Working Memory*;* *B* is a standardized metric and is analogous to standardized beta. * $p < .05$, ** $p < .01$, *** $p < .001$

Table 3.8

Regression Results for Reading Variables with Training Group as the Predictor, Pre-Training Performance as a Covariate, and Post-Training Performance as the Outcome

Outcome	Predictor Variable	*B* (SE)	95% CI *B*	*t*	Fit
TOWRE SWE Post-Training	(Intercept)	0 (0.11)	-0.23, 0.23	.00	
	TOWRE SWE Pre-Training	0.83 (0.12)	0.59, 1.07	7.18***	
	Training Group	0.01 (0.11)	-0.22, 0.25	.11	
					$R^2=0.67$***
TOWRE PDE Post-Training	(Intercept)	-0.01 (0.12)	-0.24, 0.23	-.05	
	TOWRE PDE Pre-Training	0.8 (0.12)	0.56, 1.05	6.84***	
	Training Group	-0.15 (0.12)	-0.39, 0.09	-1.31	
					$R^2=0.67$***
NDRT-RC – Reading Rate Post-Training	(Intercept)	0 (0.15)	-0.31, 0.3	-.01	
	NDRT-RC – Reading Rate Pre-Training	0.67 (0.15)	0.35, 0.98	4.31***	
	Training Group	-0.04 (0.15)	-0.35, 0.27	-.27	
					$R^2=0.46$**
NDRT-RC – % Correct Answers Post-Training	(Intercept)	-0.01 (0.18)	-0.38, 0.36	-.04	
	NDRT-RC – % Correct Pre-Training	0.37 (0.18)	-0.01, 0.75	2.01	
	Training Group	-0.21 (0.18)	-0.58, 0.17	-1.15	
					$R^2=0.21$

Note: B is a standardized metric and is analogous to standardized beta. WM training group n=13, Active control group n=14;
* $p < .05$, ** $p < .01$, *** $p < .001$

Table 3.9

Description of Expectation Rating Composites/Categories

Composite/Category	Outcome Measure	Expectations Questionnaire Item
Working Memory Maintenance	DalCAB Item Memory	The computer task where you remember a series of playing cards and determine if a subsequently presented card was present in the series.
	DalCAB Location Memory	The computer task where you remember the location of a series of playing cards and determine if a subsequently presented card location was one of the locations presented in the series.
Working Memory Executive	Operation Span	The computer task where you do both mathematical equations and remember words.
	Symmetry Span	The computer task where you judge matrix symmetry and remember red square locations
	Reading Span	The computer task where you read sentences and remember letters.
Reading	TOWRE SWE	The single word speed reading task
	TOWRE PDE	The made-up word speed reading task
	NDRT-RC	The passage-reading comprehension task.
Concentration	N/A	Concentrate during school activities (e.g., studying, in class, doing school work).
		Concentrate while reading.
Strategy Use	N/A	Use concentration strategies while reading.
		Use strategies to do well in school.
Confidence in Abilities	N/A	Feel more confident about your ability to understand class materials and do well on academic tasks.

Figure 3-1

CONSORT flow chart

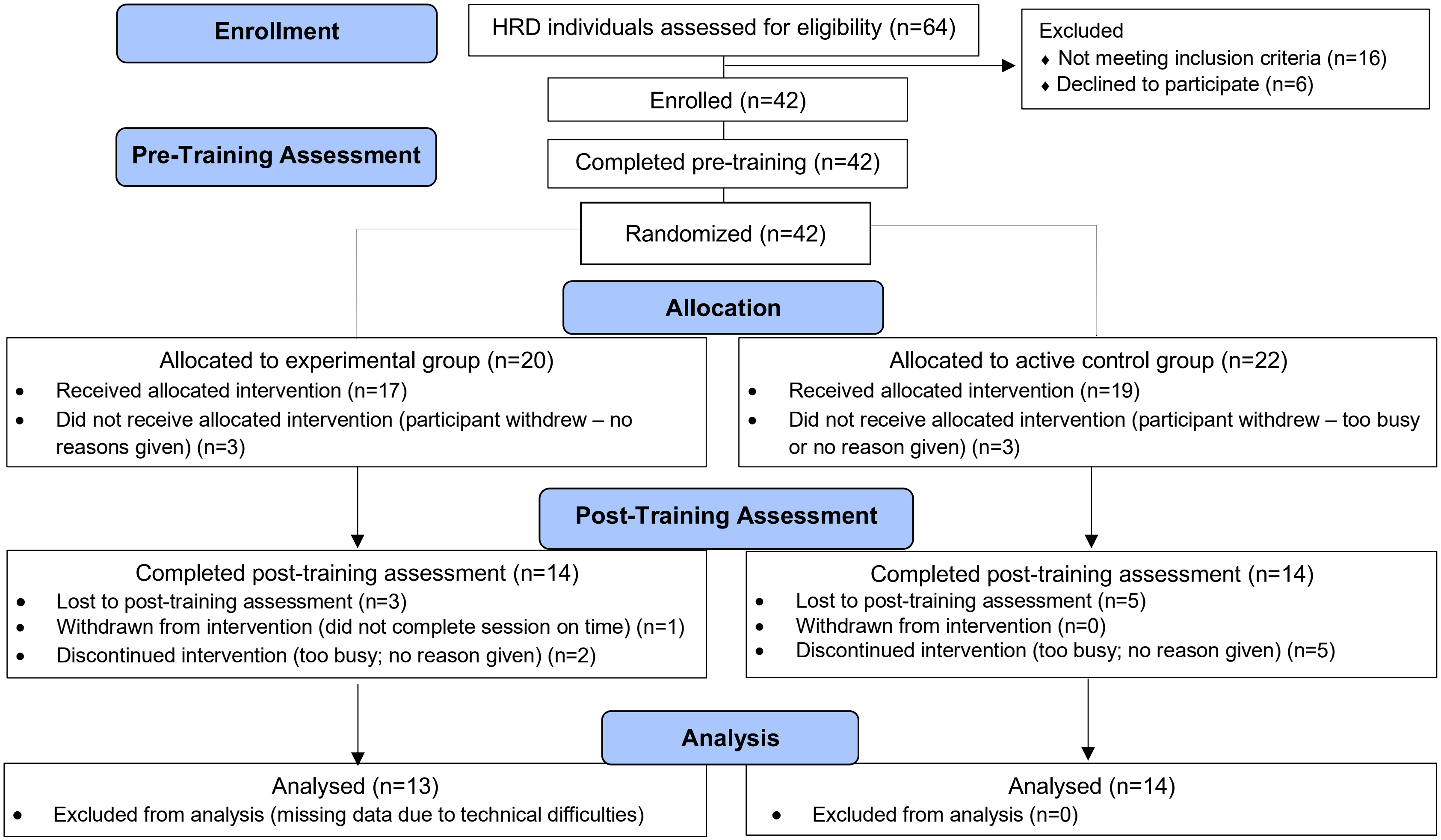
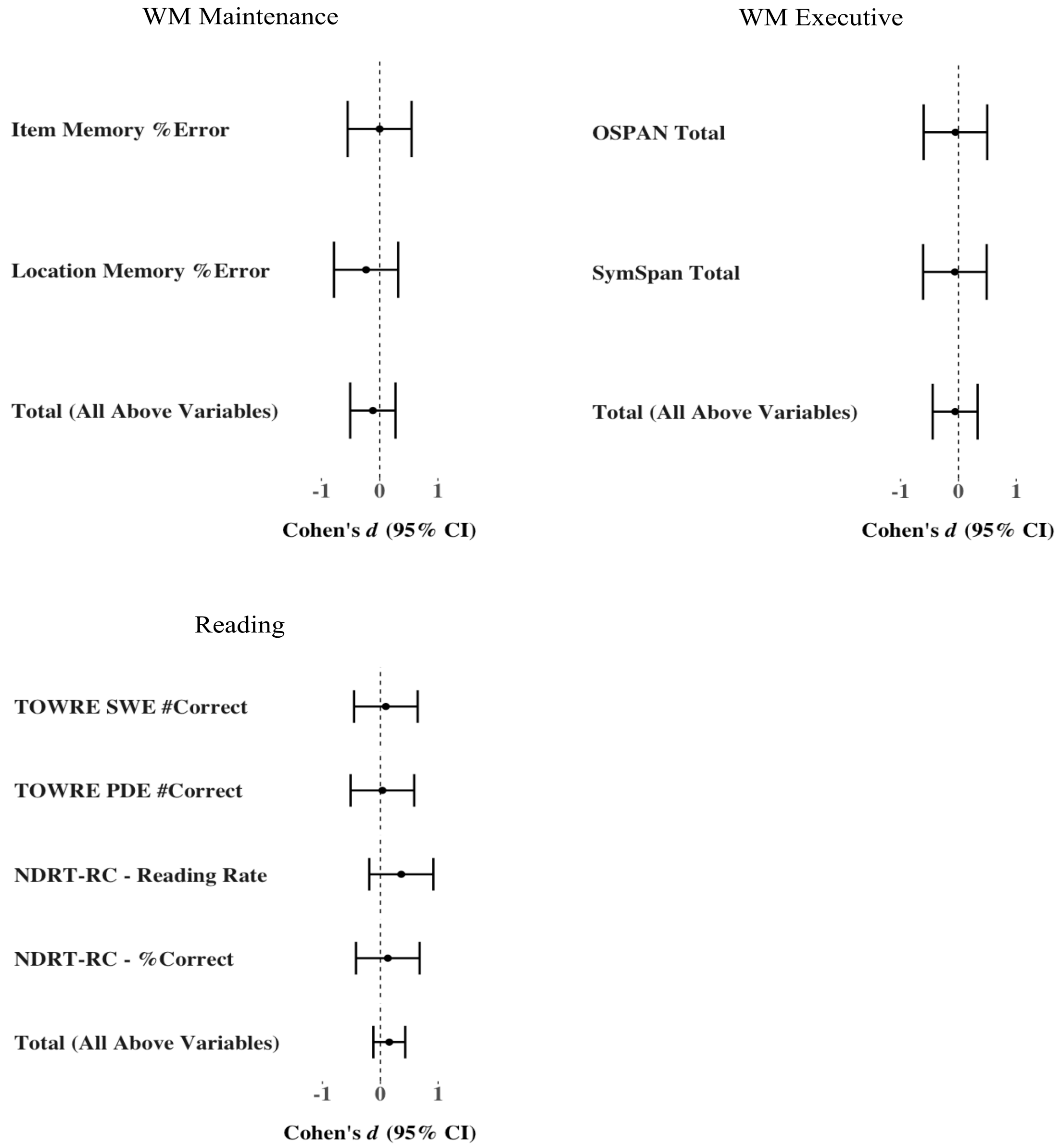


Figure 3-2

Forest plots of Cohen's d for factors of WM maintenance, WM executive, and reading between HRD participants who did and did not complete the training study



Note: Cohen's *d* to the right of the dashed line (i.e., 0) indicate better performance by HRD participants who completed the training study. The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). IM=Item Memory; LM=Location Memory; PDE= Phonemic Decoding Efficiency; RC=Reading Comprehension; RT=Reaction Time; SWE=Single Word Efficiency.

Figure 3-3

Individual performance on the WM training task: Average n-level achieved by session

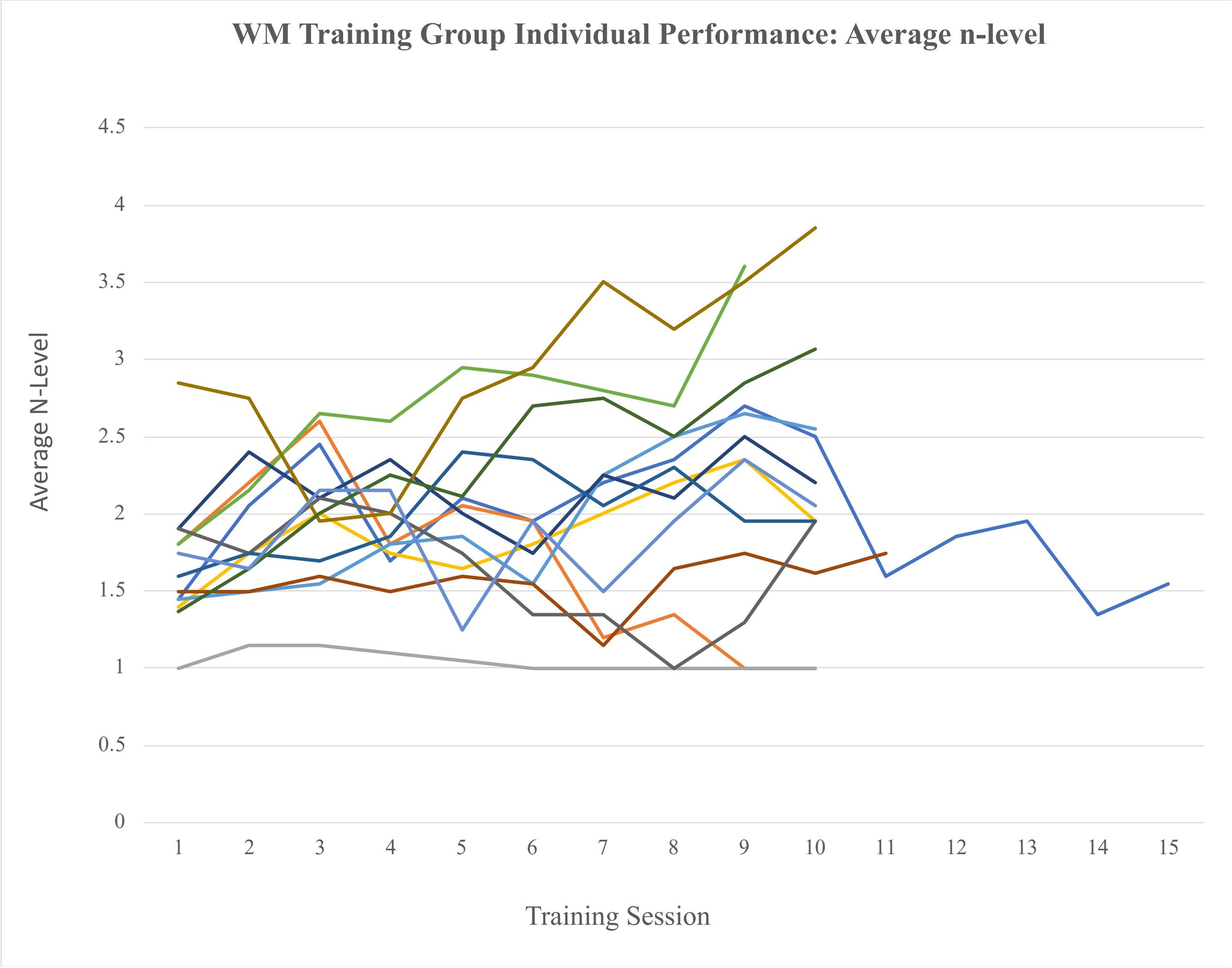


Figure 3-4

Individual performance on the active control task: Average reaction time achieved by session

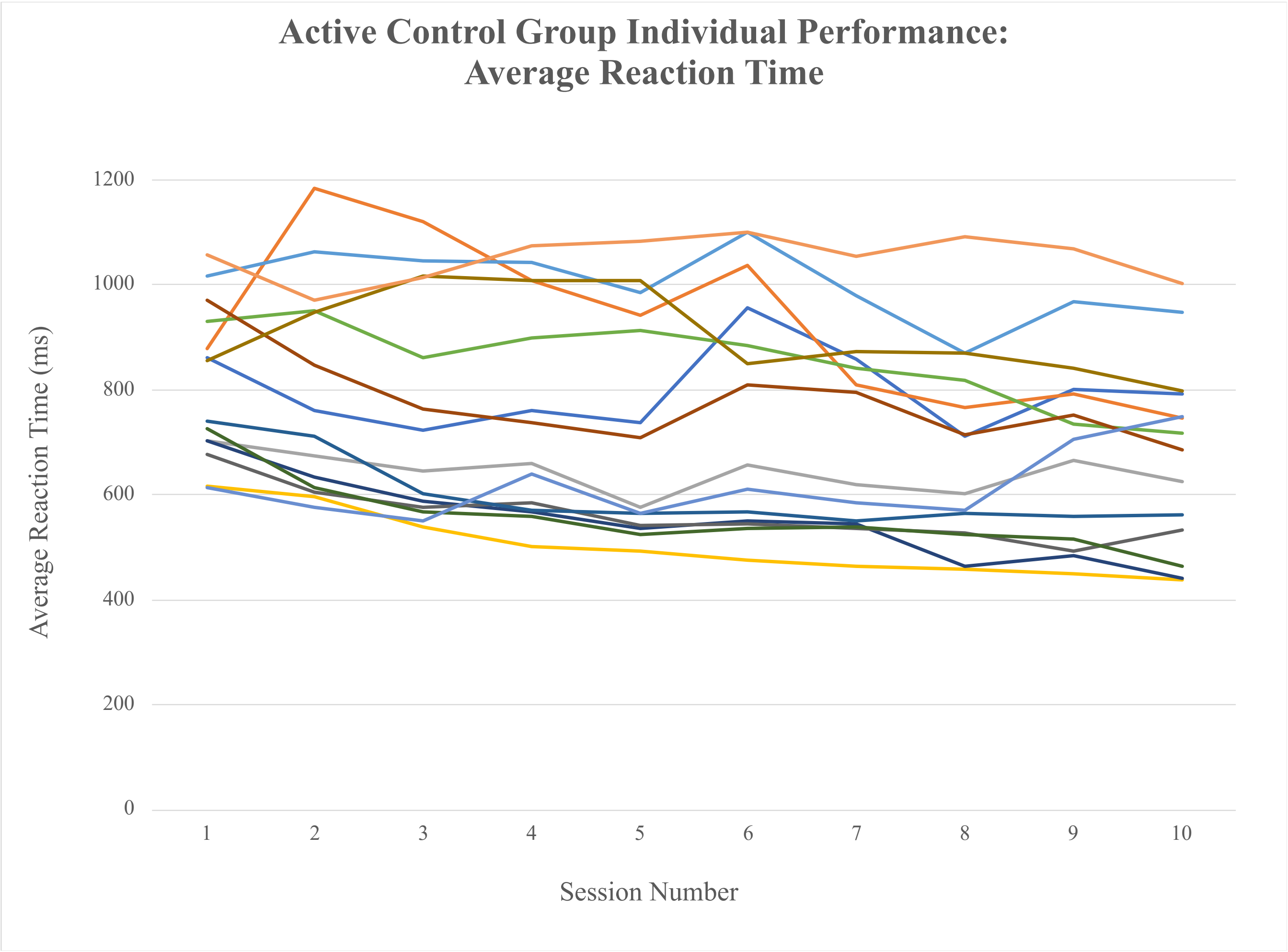


Figure 3-5

Individual performance on the active control task: Average accuracy achieved by session

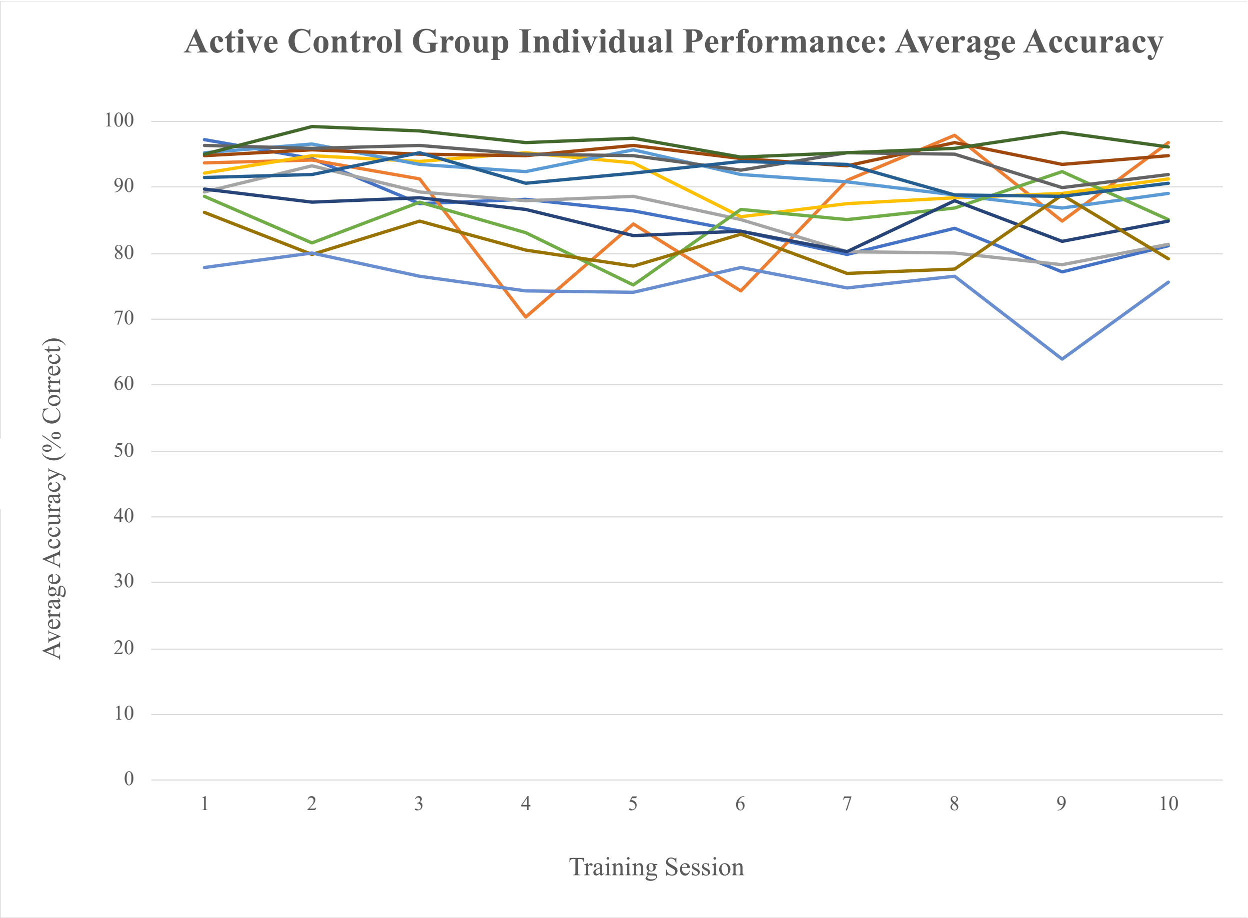
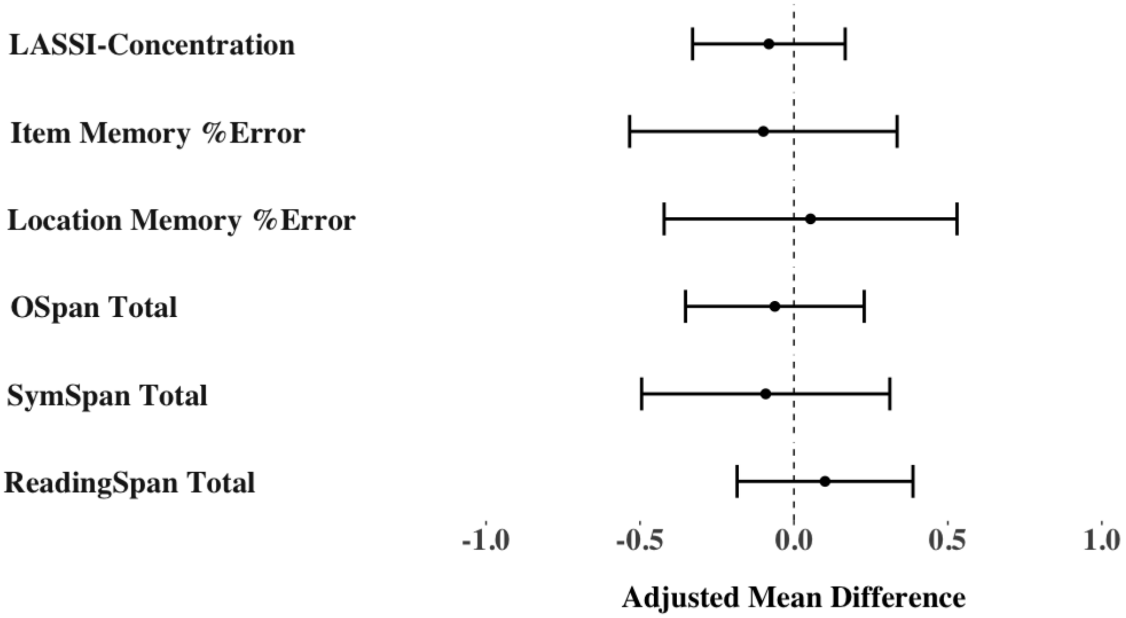


Figure 3-6

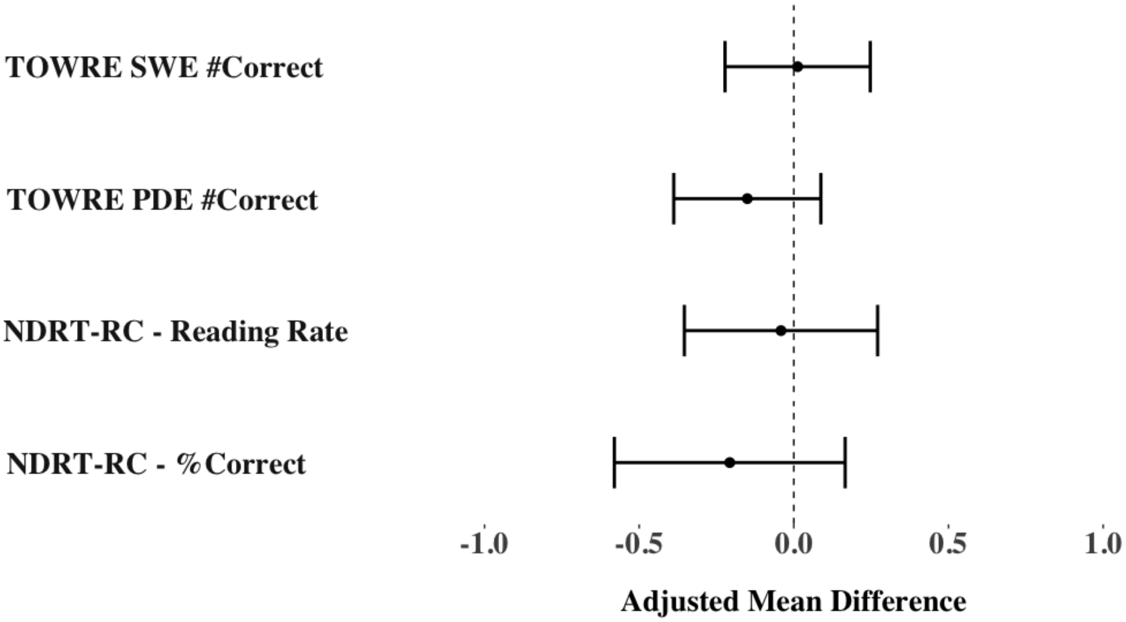
Forest plots of beta (B) for training group as a predictor of post-training performance on the outcome variables from the self-report measure of attention on academic tasks, working memory maintenance measures, and WM executive measures, with pre-training performance as a covariate



Note: Adjusted mean differences to the right of the dashed line (i.e., 0) indicate better performance by the WM training group on the post-training assessment when accounting for performance on the pre-training assessment (i.e., pre-training assessment as a covariate). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). RT=Reaction Time.

Figure 3-7

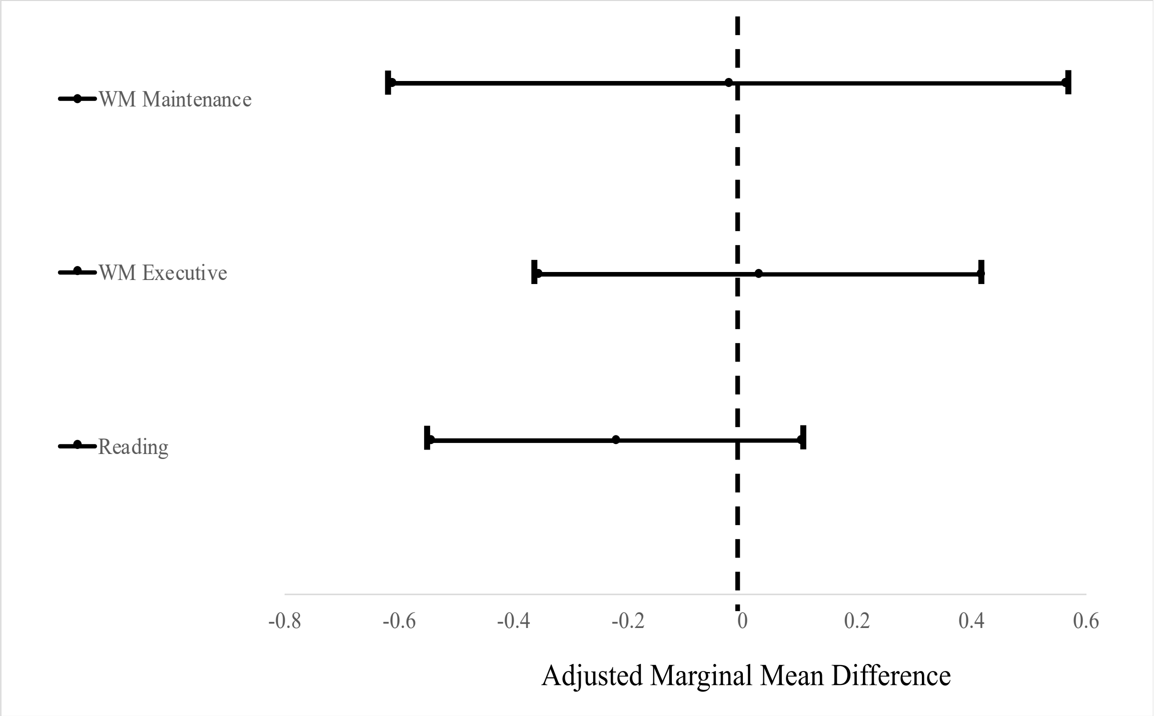
Forest plots of beta (B) for training group as a predictor of post-training performance on the outcome variables from the reading measures with pre-training performance as a covariate



Note: Adjusted mean differences to the right of the dashed line (i.e., 0) indicate better performance by the WM training group on the post-training assessment when accounting for performance on the pre-training assessment (i.e., pre-training assessment as a covariate). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*). PDE= Phonemic Decoding Efficiency; RC=Reading Comprehension; SWE=Single Word Efficiency.

Figure 3-8

Adjusted mean differences by factor calculated from linear mixed models



Note: Mean differences to the right of the dashed line (i.e., 0) indicate better performance by the WM training group on the post-training assessment when accounting for performance on the pre-training assessment (i.e., pre-training assessment as a covariate). The error bars represent 95% confidence intervals (CI). If error bars do not cross zero, it indicates a significant difference between groups and is indicated by an asterisk (*).

Chapter 4: General Discussion

University students with a history of reading difficulties (HRD) have ongoing reading problems (Deacon et al., 2012) and academic challenges (Bergey et al., 2017; Chevalier et al., 2017). Understanding the mechanisms underlying these students' reading difficulties and identifying ways to improve their reading performance is critical given the importance of reading to academic achievement (Gottfried et al., 2015; Reder, 1999; Snow & Strucker, 1999). Thus, the overall objective of this dissertation was to extend previous work characterizing HRD students' cognitive abilities and identifying effective ways of supporting them in academic settings. Specifically, this dissertation aimed to characterize the attention and working memory (WM) abilities of HRD students, relative to their peers without a history of reading difficulties (NRD), and to determine the relationships between those abilities and reading performance in both HRD and NRD students (see Study 1). Attention and WM are multifaceted higher-order cognitive functions that have been conceptualized as being important for reading (Butterfuss & Kendeou, 2017; Dehn, 2008; Vidyasagar & Pammer, 2010) with empirical support from longitudinal and cross-sectional studies for the same (e.g., Arrington et al., 2014; Follmer, 2018; Hannon, 2012; Jones et al., 2008; Larsen et al., 2022; Mahé et al., 2014; Nicolson & Fawcett, 2000; Smith-Spark et al., 2003, 2016; Swanson & Jerman, 2007). Furthermore, this dissertation aimed to determine whether remediation aimed at a cognitive function thought to be important reading performance is effective in improving HRD students' reading abilities. Based on the findings from Study 1, empirical evidence for gains on reading outcomes following computerized WM training (e.g., Artuso et al., 2019; Chein & Morrison, 2010), and theorized mechanisms of transfer from cognitive training (Dahlin et al., 2008; von Bastian et al., in press; von Bastian & Oberauer, 2014), this thesis evaluated whether computerized WM training is effective in improving HRD students' WM and reading abilities.

To achieve the aims of this dissertation, I carried out two studies. In Study 1, I investigated the reading, attention, and WM abilities of 51 HRD students in comparison to 51 university students without a history of reading difficulties (NRD). To evaluate reading ability, participants were given measures of decoding, reading comprehension, and reading rate. Applying Posner and colleagues' model of attention (Petersen & Posner, 2012), the following attention functions were evaluated: vigilance processing speed, vigilance decisions speed, orienting attention, attentional control switching/shifting, attentional control interference control/conflict resolution, and attentional control response inhibition. Applying Baddeley's (2010, 2012) multicomponent model of WM, verbal and visuospatial measures that primarily tapping into the domain-specific storage components of WM (hereafter referred to as WM maintenance measures) were given, along with verbal and visuospatial WM measures that placed greater demands on processes carried out by the domain-general central executive component of WM (hereafter referred to as WM executive measures). Briefly, consistent with previous findings of other researchers (e.g., Bergey et al., 2017; Deacon et al., 2012), I found that HRD students have weaknesses in decoding and reading comprehension skills and they self-report greater difficulties maintaining their attention on academic tasks. I also found that HRD students' self-reported concentration difficulties were accompanied by weaker performance than NRD students on objective measures of attention and WM (described in greater detail below).

In Study 1, with the same samples of HRD and NRD students, I also evaluated the unique and combined associations between the attention functions and reading, between verbal and visuospatial WM maintenance measures and reading, and between verbal and visuospatial WM executive measures and reading. These relationships were evaluated separately for decoding and reading comprehension outcomes. Briefly, I found that across both groups (i.e., when combined), response inhibition was associated with better decoding performance. In the NRD group, successful and efficient decoding ability was associated with greater ability to remain vigilant/on-task and to quickly make decisions, and better decoding and reading comprehension was associated with WM performance in the verbal domain. In contrast, in the HRD group, only WM was significantly related to reading performance and these relationships were not restricted to one domain (i.e., both visuospatial and verbal).

In Study 2, I evaluated the effectiveness of 10 sessions of training on an adaptive dual *n*-back task versus training on an active control task at improving their WM and reading performance. Briefly, I found that training task performance was highly variable amongst the HRD participants and participants made smaller gains on the adaptive WM training task than those expected based on studies with healthy young adults not selected for learning or cognitive difficulties (e.g., Jaeggi et al., 2010; Küper & Karbach, 2016; Redick et al., 2013; Rhodes & Katz, 2017; Salminen et al., 2012). There was no evidence for transfer to untrained WM measures, nor to decoding or reading comprehension tasks.

The findings from this dissertation uncovered novel information regarding HRD students' current cognitive challenges, revealing that they may have problems with various aspects of attention and WM. Small group differences between HRD and NRD students on measures of attention (i.e., Cohen's *d* ranging from 0.37 to 0.44) revealed that HRD students may have problems with *vigilance* while making judgments and choices, with *orienting* their visual attention, and with *attentional control* for response inhibition. Moreover, HRD students performed worse than their NRD peers on both visuospatial and verbal WM executive measures that placed high demands on the domain-general central executive component of Baddeley's model of WM. Group differences across the WM executive measures were the largest of all the attention and WM measures given (i.e., d = 0.67). Notably, HRD students did not perform differently than NRD students on WM maintenance measures that involved primarily the domain-specific short-term storage systems of WM (i.e., the phonological loop and the visuospatial sketchpad of Baddeley's model of WM). This pattern of findings suggests that HRD students' WM functioning is limited most by the central executive system rather than capacity of the WM storage systems. In other words, it appears that HRD students' WM performance is limited by weaknesses in attentional control rather than their WM storage capacity. Providing further indication that HRD students may have problems with attentional control, I found that HRD students had difficulty learning effectively on a complex dual-modality WM executive task (i.e., a dual *n*-back task) in Study 2. Thus, HRD students' self-reported concentration difficulties likely reflect real attentional challenges, at minimum in contrast to NRD students, with their greatest difficulties appearing to involve attentional control processes in WM.

These findings offer some support for the idea that university students who self-identify as having a history of reading difficulties and adults diagnosed with dyslexia represent the same underlying population along a continuum. In previous work, HRD students have been found to have similar levels of phonological awareness, decoding, and timed reading comprehension as university students diagnosed with LD(s), and both groups of students have been found to have weaker skills in all three than NRD students Difficulties with phonological awareness, decoding, and reading comprehension are all common characteristics of individuals with dyslexia (Roitsch & Watson, 2019). In Study 1 of this thesis, I found that the aspects of attention and WM that were weaker in HRD students relative to their NRD peers were ones that have been shown previously to be weak in adults and adolescents diagnosed with dyslexia compared to their peers without dyslexia (e.g., M. W. Jones et al., 2008; Nicolson & Fawcett, 2000; Smith-Spark et al., 2003, 2016). The HRD students in Study 1 did not, however, display any problems with other aspects of attention and WM found to be impacted in dyslexia, including maintenance of verbal information in WM and interference control/conflict resolution (e.g., Horowitz-Kraus & Breznitz, 2009; Mahé et al., 2014). These findings suggest that in addition to reading skills and phonological awareness, HRD students may also have attention and WM challenges similar to, but less extensive than, those previously identified in adolescents and adults diagnosed with dyslexia. Encouragingly, the findings of Study 1 also provide support for the use of the ARHQ-R as a tool for identifying university students with current reading and cognitive challenges similar to their diagnosed peers, but who may not meet conventional definitions of learning disabilities. As a sample of university students with recent diagnoses of dyslexia was not evaluated on the same measures, only speculations about attentional commonalities between HRD students and their diagnosed peers can be made. Direct comparisons of the attention and WM abilities of HRD students and their peers with recent diagnoses of dyslexia will be an important next step towards characterizing the cognitive abilities of HRD students and contextualizing them within a continuum framework of dyslexia.

In Study 1, I found that the patterns of associations between reading skills and WM in HRD and NRD students shared some similarities with those found previously in typically developing individuals during early and later stages of reading development, respectively. Based on findings from Peng et al. (2018) meta-analysis of 197 studies, associations of WM associations with reading performance spans multiple domains within WM in young children (i.e., before grade 4) who are likely in the process of acquiring foundational skills, verbal knowledge, and lexical representations. Peng et al.

found that after grade 4, when foundational reading skills and knowledge are presumably stronger, associations between WM and reading become domain-specific to verbal material. The authors speculated that this was because readers at later stages of reading development lean on the retrieval of lexical and verbal knowledge from long-term memory for reading performance. As expected for adult readers with a typical trajectory of reading development, I found that the decoding and reading comprehension performance of NRD students were positively associated with WM performance in the verbal domain and not in the visuospatial domain. In contrast, the decoding and reading comprehension performance of HRD students was positively associated with WM performance in both verbal and visuospatial domains, a pattern more similar to those observe in children in earlier stages of reading development. The development of HRD students' reading and WM skills may have been hindered, perhaps due to early weaknesses in WM, reading, or both. This would be consistent with a recently proposed bidirectional theory of academic learning cognition suggesting that academic learning (e.g., learning to read) draws on cognitive abilities (e.g., working memory and reasoning) and in turn, strengthens those cognitive abilities (Peng & Kievit, 2020). To further investigate whether the patterns between WM and reading in HRD students observed in this dissertation are reflective of stunted development, future studies may directly compare the patterns of those relationships in HRD university students to those found in children learning to read (i.e., before grade 4).

Positive associations found in HRD students between visuospatial WM maintenance performance and both decoding and reading comprehension performance may also reflect the use of visual memory strategies. For instance, to aid with reading comprehension, written information could be converted into visualized images to help maintain the information in mind. It has been proposed that adults with dyslexia use a similar strategy to aid their reasoning (Bacon & Handley, 2010, 2014). Visual imagery can help to reduce the cognitive load placed on WM during reading, by organizing details in the text into meaningful chunks (Woolley & Hay, 2004).

Although visual strategies may support HRD students' reading performance, it is clear from their current deficits in decoding and reading comprehension in adulthood (Deacon et al., 2012) that more is needed for them to overcome or compensate for their reading difficulties. Many HRD students may not recognize that they need additional help or have a repertoire of effective reading strategies. In Study 1, despite weaknesses in decoding relative to their NRD peers, HRD students read a text for the purposes of comprehension at the same rate as NRD students and showed worse untimed reading comprehension. This pattern is notable in contrast to Deacon et al.'s (2012) findings that university students with a recent diagnosis of a learning disability (LD) read at a slower rate than HRD students, but have untimed reading comprehension in the normal range. Students with LD's prioritization of their comprehension of text over reading speed may reflect a reading strategy that they generated or were taught in order to address their known reading impairments. Since only a minority of HRD university students receive a formal diagnosis of an LD (i.e., fewer than 20%; Bergey et al., 2018; Deacon et al., 2012), they are less likely to be offered targeted instruction or to seek out information on effective compensatory reading strategies. Thus, in addition to targeting cognitive functions found to be weaker in HRD students and associated with their reading performance (e.g., WM), reading-specific strategy instruction may help HRD students compensate better for their reading difficulties and cognitive inefficiencies.

In Study 2, I found that HRD students' weaknesses in attentional control and WM may have interfered with their abilities to learn on the training task. They trained on a WM training task that taxed attentional control processes of the central executive and that would engage both temporary storage systems of WM (i.e., the phonological loop and the visuospatial sketchpad). Specifically, they trained on a dual *n*-back training task that required control of attention for continuous updating of information in the verbal-auditory and visuospatial storage systems of WM, simultaneous (Gajewski et al., 2018; Jaeggi et al., 2008). I selected a WM training task that placed high demands on the central executive system of WM (hereafter referred to as WM executive tasks) because the strongest empirical support for transfer to reading outcomes following WM training on WM executive tasks (e.g., Artuso et al., 2019; Henry et al., 2014) and because I found that HRD students' demonstrated weaknesses relative to their NRD peers on WM executive tasks. Moreover, I selected a training task that engaged both temporary storage systems of WM because I found that HRD students' WM weaknesses spanned both the visuospatial and verbal domains and because their reading skills were associated with

WM in both visuospatial and verbal domains. Unfortunately, the training task may have been too challenging for their baseline WM abilities, as reflected by their limited gains on the training task. Additionally, although it is not known whether HRD and NRD students differ in their abilities to update information in WM, prior research has found that updating impairments are common in adults and children with reading problems (Carretti et al., 2005; Cornoldi et al., 2012; Palladino et al., 2001; Swanson et al., 2006). Thus, if HRD students also have weaknesses in updating, the updating demands of the training task may have made the task especially challenging for them. Furthermore, HRD students' accuracy on the visual stimulus task was significantly lower than on the auditory stimulus task and did not improve over the course of training, emphasizing HRD students' difficulties with visuospatial WM. The training difficulties observed in HRD students in Study 2 highlight the need of researchers to consider HRD students' unique cognitive challenges and broader needs when designing interventions.

Perhaps a less complex or demanding WM training program would be more suitable for HRD students. Comparable transfer effects have been found following training on single and dual *n*-back tasks (e.g., Jaeggi et al., 2010, 2014; for meta-analyses see Au et al., 2015; Soveri et al., 2017). Further, WM executive training tasks with visual stimuli may be better at engaging the domain-general central executive component of WM than verbal ones, and more effective at promoting transfer to reading comprehension (e.g., Chein & Morrison, 2010); therefore, HRD students may benefit more from training on a single visual *n*-back task than a verbal one. Moreover, multisensory exposure (i.e., integrated sensory information across more than one modality) has been found to aid memory and learning (for review, see Shams & Seitz, 2008) and could be applied to WM training to support training task learning and transfer. Pahor et al. (2021) found equivalent training gains in undergraduate students following approximately 6.7 hours of training on a visual-only *n*-back task and a multisensory *n*-back task. In the latter, each visual stimulus was presented with a unique associated sound. Notably, the authors also found that the multisensory training group showed significant near transfer effects to both a verbal WM maintenance task (i.e., a letter-number sequencing) and to a visuospatial WM executive task (i.e., Symmetry Span), whereas no near transfer was observed in the visual-only training group. Thus, a multisensory *n*-back training task, with visuospatial stimuli accompanied by non-verbal auditory stimuli may offer additional benefits to training WM in HRD students.

In Study 2, I found no evidence of near transfer effects to untrained WM maintenance and WM executive measures, nor far transfer effects to decoding and reading comprehension. One possibility is that the HRD participant who practiced the adaptive training task did not improve enough on the training task for transfer to occur. Some researchers have found that training task performance is linked to training effects (e.g., Bürki et al., 2014; Chein & Morrison, 2010; Jaeggi et al., 2011); however, Au et al. (2015) failed to find evidence of such a relationship in their meta-analysis of *n*-back WM training studies with healthy adults between the ages of 18 and 50 years. It is not known whether there is a minimum degree of improvement on *n*-back training tasks that is necessary for transfer to occur; thus, it is not known whether transfer is expected following significant but limited gains on the training task like those found in HRD in Study 2.

Alternatively, practice on *n*-back tasks, like the one used in this thesis, may not result in gains in reading skills in HRD students. In a review by von Bastian and Oberauer (2014), the authors described two theorized mechanisms of transfer: (1) increased WM capacity and (2) enhanced efficiency in the use of existing WM resources. In the former, training leads to increases in the amount of information that can be held in WM and transfer occurs in activities that utilize the additional resources. In the latter, it is theorized that individuals acquire new knowledge and skills from training that allow them to use their WM resources more efficiently. With increased WM efficiency, transfer is expected to occur only when the same knowledge and skills can be applied to other activities. It is clear, from the lack of near transfer in HRD students to untrained WM tasks, that training on the dual *n*-back task did not expand HRD students' WM capacities. Moreover, the lack of near and far transfer to untrained WM tasks and to reading outcomes, respectively, indicates that if practice on the training task resulted in generation of new strategies or cognitive routines, they were not applicable (or not effectively applied) to the outcome activities. Furthermore, intervention-specific features (e.g., paradigm(s), intensity, dose, etc.) and individual characteristics (e.g., age, baseline cognitive ability, motivation and personality traits) may also influence training and transfer and must therefore be considered when determining what training approaches are appropriate and for whom (for review, see von Bastian & Oberauer, 2014).

Other approaches to training WM and attentional control processes affected in HRD students may be more effective at improving their reading skills than training on classical WM training tasks, such as interventions that incorporate features of action video games. Research on the benefits of action video games to several cognitive domains (Bediou et al., 2018) has greatly strengthened our knowledge and understanding of the principles of learning that facilitate learning on new tasks (Bavelier et al., 2012). Action video games include features known to facilitate new learning: keeping players at a level difficulty that is neither too challenging or too easy, engaging players in rich environments with ever changing demands and goals, and including rewards that incentivise effort and stimulate the rewards system of the brain (Bavelier & Green, 2019). Further, they include three game mechanics that have been proposed to be necessary for transfer cognitive outcomes: the need to quickly make decisions and motor responses, the need to engage various attentional control processes, and the need to switch between different attentional control processes (Bavelier & Green, 2019). As HRD students present with relative weaknesses in WM, and also in various aspects of attention that are believed to be engaged in action video games (i.e., maintaining a state of readiness to make quick decisions, orienting attention, and attentional control), they may benefit more from an intervention that applies the mechanics of action videos games to a cognitive intervention that engages multiple control functions.

In a recent study, Pasqualotto et al. (2022) investigated the effects of an intervention that incorporate features of action video games on reading skills in a sample of 151 Italian-speaking typical readers between the ages of 8 and 12 years old. Children received 12 hours of practice on either the active control task (i.e., a programming game) or the experimental group task that consisted of eight minigames adapted from classic measures of attentional control and executive functions (including WM) into an action video game-like environment. The authors found that the children in the experimental group showed greater gains than the active control group on measures of attentional control, and also on their reading speed and accuracy (i.e., words, pseudowords, and text). These training benefits remained at 6-month follow-up. They also found that the experimental group showed small benefits in academic achievement in the school subject of Italian, 18 months following training; the active control group did not. Pasqualotto et al.'s findings are very exciting as they indicate that attentional control and WM training can benefit both experimental assessments, as well as real-world academic outcomes; however, more research on this topic is needed, especially in adult learner populations, such as HRD students and other students with learning difficulties.

Findings of broad transfer following training on action video games (Bediou et al., 2018) have led some researchers to propose an alternative mechanism to the capacity-efficiency model underlying transfer that may be important to consider when designing a cognitive training study: learning to learn (Bavelier et al., 2012). According to this model, training can enhance a person's ability to learn new tasks. In support of this theory, Zhang et al., (2021) found that adults who trained on action video games ($M_{\text{Age}} =$ 22.8 years) learned faster than compared to active controls ($M_{\text{Age}} =$ 23 years) on a perception task and on a WM task. If training facilitates learning on new tasks instead of, or in addition to, enhancing the capacity or efficiency of trained cognitive functions, then measuring outcomes of interest at one time point, as I did in this thesis, may not sufficiently capture what is gained from cognitive training. To my knowledge, the learning to learn theory has not been evaluated using conventional cognitive training paradigms like the dual *n*-back task used in Study 2. Future cognitive training studies should consider including both immediate post-training performance and learning rates on outcomes for cognitive training studies. Doing so may better identify the benefits of cognitive training and expand our understanding of the mechanisms underlying transfer.

The findings of this dissertation provide a greater understanding of the reading and cognitive challenges experienced by HRD university students and of how their attention and WM challenges may impact their abilities to effectively learn on cognitively demanding tasks. Although this work did not identify an intervention that can be used to improve HRD students' reading skills, it provided important insights into the intervention characteristics that are not suitable or feasible for those students and guidance towards alternative approaches that may be more effective. This work was successful in achieving its goal of extending previous work on characterizing HRD university students' abilities and working to identify effective ways of supporting them in academic settings.

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Appendix A: Adult Reading History Questionnaire – Revised (ARHQ-R)

Elementary School Scale

Read each of the response that best describes you. Please choose only one response per question.

1. How much difficulty did you have learning to read in elementary school?

0 None
1 Not much
2 Some
3 Quite a bit
4 A great deal

2. How much extra help did you need when learning to read in elementary school?

0 No help
1 Help from friends
2 Help from teachers/parents
3 Tutors or special class for one year
4 Tutors or special class for 2 or more years.

3. How would you compare your reading skill to that of others in your elementary classes?

0 Clearly above average
1 Somewhat above average
2 Average
3 Somewhat below average
4 Clearly below average

4. Which of the following most nearly describes your attitude toward reading as a child?

0 Very positive
1 Somewhat positive
2 Neutral
3 Somewhat negative
4 Very negative

5. When you were in elementary school, how much reading did you do for pleasure?

0 A great deal
1 Quite a bit
2 Some
3 Not much
4 None

6. How would you compare your reading speed in elementary school with that of your classmates?

0 Clearly above average
1 Somewhat above average
2 Average
3 Somewhat below average
4 Clearly below average

7. How much difficulty did you have learning to spell in elementary school?

0 None
1 Not much
2 Some
3 Quite a bit
4 A great deal

8. When you were in elementary school, how many books did you read for pleasure each year?

0 More than 10
1 6 to 10
2 3 to 5
3 1 to 2
4 None

Appendix B: Summary of Research Findings on HRD University Students' Reading Skills

Decoding

Oral reading of written words and non-words with accuracy and/or fluency

Paper	**Measure**	**Comparison groups**	**Finding**	**Effect Size (*d*)**
Deacon et al. (2006)	WRMT-R Word Identification (Word Reading)	HRD (*n*=27) vs. NRD (typical ARHQ-R cut-offs not used for NRD – based more generally on self-report) (*n*=28)	NRD > HRD Grade Equivalence (GE): HRD GE 11 – authors noted that standardized administration was not followed	1.51***
Deacon et al. (2006)	WRMT-R Word Attack (Pseudoword Reading)	HRD (*n*=27) vs. NRD (typical ARHQ-R cut-offs not used for NRD – based more generally on self-report) (*n*=28)	NRD > HRD Grade Equivalence (GE): HRD GE 7 – authors noted that standardized administration was not followed	1.12***
Corkett et al. (2006)	WRMT-R Word Identification (Word Reading)	HRD (*n*=29) vs. NRD (*n*=38)	NRD > HRD	Insufficient information available.
Corkett et al. (2006)	WRMT-R Word Attack (Pseudoword Reading)	HRD (*n*=29) vs. NRD (*n*=38)	NRD > HRD	Insufficient information available.
McGonnell et al. (2007)	WRMT-R Word Identification (Word Reading)	HRD (*n*=21) vs. NRD (*n*=21)	NRD > HRD	1.57**
Parrila et al. (2007)	WRMT-R Word Identification (Word Reading)	HRD (*n*=28 – 10 with recent diagnosis (HRD-D) rest w/o (HRD-ND) vs. NRD (*n*=27)	NRD > HRD Grade Equivalence (GE): HRD GE 12; NRD GE 17	1.59***
Parrila et al. (2007)	Castles and Coltheart's (1993) Regular Word Reading	HRD (*n*=28 – 10 with recent diagnosis (HRD-D) rest w/o (HRD-ND) vs. NRD (*n*=27)	Accuracy ceiling effect NRD > HRD for RT HRD-ND = HRD-D – for RT	1.09*** (RT)
Parrila et al. (2007)	Castles and Coltheart's (1993) Irregular Word Reading	HRD (*n*=28 – 10 with recent diagnosis (HRD-D) rest w/o (HRD-ND) vs. NRD (*n*=27)	NRD > HRD for Accuracy NRD > HRD for RT HRD-ND = HRD-D – both Acc and RT	0.81** (Acc) 1.22*** (RT)

Paper	**Measure**	**Comparison groups**	**Finding**		**Effect Size (*d*)**
Parrila et al. (2007)	WRMT-R Word Attack (Pseudoword Reading)	HRD (*n*=28 – 10 with recent diagnosis (HRD-D) rest w/o (HRD-ND) vs. NRD (*n*=27)	NRD > HRD HRD-ND = HRD-D Grade Equivalence (GE): HRD GE 7; NRD GE 12		1.30***
Parrila et al. (2007)	Castles and Coltheart's (1993) Pseudoword Reading	HRD (*n*=28 – 10 with recent diagnosis HRD-D rest w/o HRD-ND)vs. NRD (*n*=27)	NRD > HRD for Accuracy NRD > HRD for RT HRD-ND = HRD-D both Acc and RT		1.24*** (Acc) 1.39*** (RT)
Kemp et al. (2009)	WRMT-R Word Identification (Word Reading)	HRD (*n*=29) vs. NRD (*n*=28) – matched raw scores on Raven's Matrices and spelling WRAT-3	NRD > HRD		1.55***
Kemp et al. (2009)	WRMT-R Word Attack (Pseudoword Reading)	HRD (*n*=29) vs. NRD (*n*=28) – matched raw scores on Raven's Matrices and spelling WRAT-3	NRD > HRD		1.33***
Deacon et al. (2012)	WRMT-R Word Identification (Word Reading)	HRD (*n*=31) vs. NRD (*n*=33) HRD vs. LD (i.e., diagnosed with LD or dyslexia; *n*=20) LD vs. NRD	Grade Equivalence (GE): HRD GE 11.73; LD GE 11.69; NRD GE 15.09	NRD>HRD	1.07**
				NRD>LD	1.09**
				HRD=LD	0.08
Deacon et al. (2012)	TOWRE Sight Word Efficiency	HRD (*n*=31) vs. NRD (*n*=33) HRD vs. LD (i.e., diagnosed with LD or dyslexia; *n*=20) LD vs. NRD	Grade Equivalence (GE): HRD GE 9.6; LD GE 9; NRD GE 11.8	NRD>HRD	0.91**
				NRD>LD	1.12**
				HRD=LD	0.35
Deacon et al. (2012)	TOWRE Pseudoword Reading Efficiency	HRD (*n*=31) vs. NRD (*n*=33) HRD vs. LD (i.e., diagnosed with LD or dyslexia; *n*=20) LD vs. NRD	Grade Equivalence (GE): HRD GE 8; LD GE 7.2; NRD GE 12.6	NRD>HRD	1.20**
				NRD>LD	1.68**
				HRD=LD	0.27
Hebert et al. (2018)	TOWRE Sight Word Efficiency	HRD (*n*=43) vs. NRD (*n*=124)	NRD > HRD		0.73***
Hebert et al. (2018)	TOWRE Pseudoword Reading Efficiency	HRD (*n*=43) vs. NRD (*n*=124)	NRD > HRD		1.31***

Paper	**Measure**	**Comparison groups**	**Finding**	**Effect Size (*d*)**
Metsala et al. (2019)	WRMT-R Word Identification (Word Reading)	HRD (*n*=54) vs. NRD (*n*=54) matched for age, gender, and matrix reasoning	NRD > HRD	1.04***
Metsala et al. (2019)	TOWRE Sight Word Efficiency	HRD (*n*=54) vs. NRD (*n*=54) matched for age, gender, and matrix reasoning	NRD > HRD	0.55**
Metsala et al. (2019)	TOWRE Pseudoword Reading Efficiency	HRD (*n*=54) vs. NRD (*n*=54) matched for age, gender, and matrix reasoning	NRD > HRD	0.77***
MacKay et al. (2019)	WRMT-R Word Identification (Word Reading)	HRD (*n*=46) vs. NRD (*n*=46) matched for age, gender, and matrix reasoning	NRD > HRD	0.99***
MacKay et al. (2019)	TOWRE Sight Word Efficiency	HRD (*n*=46) vs. NRD (*n*=46) matched for age, gender, and matrix reasoning	NRD > HRD Grade Equivalence (GE): HRD GE 9.9; NRD GE 10.7	0.43*
MacKay et al. (2019)	TOWRE Pseudoword Reading Efficiency	HRD (*n*=46) vs. NRD (*n*=46) matched for age, gender, and matrix reasoning	NRD > HRD Grade Equivalence (GE): HRD GE 9.9; NRD GE 10.8	0.70***

Reading Comprehension

"[T]he process of simultaneously constructing and extracting meaning through interaction and engagement with written language" (RAND Reading Study Group, 2002, p. 11)

Paper	**Measure**	**Comparison groups**	**Finding**		**Effect Size (d)**
Deacon et al. (2006)	Nelson-Denny Reading Test	HRD (*n*=27) vs. NRD (typical ARHQ-R cut-offs not used for NRD – based more generally on self-report) (*n*=28)	Timed RC Grade Equivalence (GE): HRD GE 14	NRD > HRD	0.73**
			Untimed RC	NRD = HRD	0.38
Corkett et al. (2006)	Nelson-Denny Reading Test	HRD (*n*=29) vs. NRD (*n*=38)	Timed RC	NRD > HRD	Insufficient information available.
			Untimed RC	NRD = HRD	Insufficient information available.

Paper	**Measure**	**Comparison groups**	**Finding**		**Effect Size (d)**
McGonnell et al. (2007)	Nelson-Denny Reading Test	HRD (*n*=21) vs. NRD (*n*=21)	Timed RC	NRD > HRD	1.40**
			Untimed RC	NRD > HRD	0.79*
Parrila et al. (2007)	Nelson-Denny Reading Test	HRD (*n*=28 – 10 with recent diagnosis (HRD-D) rest w/o (HRD-ND) vs. NRD (*n*=27)	Timed RC	NRD > HRD	0.76**
			Untimed RC	NRD = HRD	0.46
Kemp et al. (2009)	Nelson-Denny Reading Test	HRD (*n*=29) vs. NRD (*n*=28) – matched raw scores on Raven's Matrices and spelling WRAT-3	Timed RC	NRD > HRD HRD within normal range	0.78**
			Untimed RC	NRD = HRD	0.48
Deacon et al. (2012)	Nelson-Denny Reading Test	HRD (*n*=31) vs. NRD (*n*=33) HRD vs. LD (i.e., diagnosed with LD or dyslexia; *n*=20) LD vs. NRD	Timed RC Grade Equivalence (GE): HRD GE 11.5; LD GE 11.68; NRD GE 15.45	NRD>HRD	1.33**
				NRD>LD	1.33**
				HRD=LD	0.04
			Untimed RC	NRD > HRD	1.33***
				NRD = LD	0.04
				HRD < LD	1.16***
Hebert et al. (2018)	Nelson-Denny Reading Test – (first passage only)	HRD (*n*=43) vs. NRD (*n*=124)	No overall group differences but HRD took longer to respond to questions than NRD – even after controlling for reading rate and word reading ability		0.38
Hebert et al. (2018)	Scholastic Abilities Test for Adults	HRD (*n*=43) vs. NRD (*n*=124)			0.22
Metsala et al. (2019)	Nelson-Denny Reading Test	HRD (*n*=54) vs. NRD (*n*=54) matched for age, gender, and matrix reasoning	Timed RC	NRD > HRD	1.40***
			Untimed RC	NRD > HRD	0.96***
MacKay et al. (2019)	Nelson-Denny Reading Test	HRD (*n*=46) vs. NRD (*n*=46) matched for age, gender, and matrix reasoning	Timed RC Grade Equivalence (GE): HRD GE 12.2; NRD GE 16.2	NRD > HRD	1.44***
			Untimed RC	NRD > HRD	0.72***

Reading Rate

The speed at which an individual reads connected text (i.e., multiple related sentences)

Paper	Measure	Comparison groups	Finding	Effect Size (d)
Deacon et al. (2006)	Nelson-Denny Reading Test	HRD (*n*=27) vs. NRD (typical ARHQ-R cut-offs not used for NRD – based more generally on self-report) (*n*=28)	NRD faster than HRD Grade Equivalence (GE): HRD GE 9	0.79**
Corkett et al. (2006)	Nelson-Denny Reading Test	HRD (*n*=29) vs. NRD (*n*=38)	NRD faster than HRD	Insufficient information available.
McGonnell et al. (2007)	Nelson-Denny Reading Test	HRD (*n*=21) vs. NRD (*n*=21)	Trend only – NRD faster than HRD	0.48
Parrila et al. (2007)	Nelson-Denny Reading Test	HRD (*n*=28 – 10 with recent diagnosis (HRD-D) rest w/o (HRD-ND) vs. NRD (*n*=27)	NRD faster than HRD	0.89**
Kemp et al. (2009)	Nelson-Denny Reading Test	HRD (*n*=29) vs. NRD (*n*=28) – matched raw scores on Raven's Matrices and spelling WRAT-3	NRD faster than HRD	0.88**
Deacon et al. (2012)	Nelson-Denny Reading Test	HRD (*n*=31) vs. NRD (*n*=33) HRD vs. LD (i.e., diagnosed with LD or dyslexia; *n*=20) LD vs. NRD	NRD faster than HRD	0.68**
			NRD faster than LD	1.33**
			HRD faster than LD	0.69**
Hebert et al. (2018)	Nelson-Denny Reading Test	HRD (*n*=43) vs. NRD (*n*=124)	NRD > HRD	1.02***
Hebert et al. (2018)	Scholastic Abilities Test for Adults – time to read passage (2 passages)	HRD (*n*=43) vs. NRD (*n*=124)	NRD > HRD	0.50**
Metsala et al. (2019)	Nelson-Denny Reading Test	HRD (*n*=54) vs. NRD (*n*=54) matched for age, gender, and matrix reasoning	NRD faster than HRD	0.86***
MacKay et al. (2019)	Nelson-Denny Reading Test	HRD (*n*=46) vs. NRD (*n*=46) matched for age, gender, and matrix reasoning	NRD faster than HRD	0.86***

Appendix C: Description of Attention Tasks Mentioned in the Thesis, Organized Using Posner and Colleagues' Model Of Attention

Posner's Attention Network Component	**Task**	**Task Description**	**Citation(s) mentioned in this thesis that used the task**
Vigilance/ Alerting Component	Warning signal tasks (e.g., Attention Network Test (ANT) alerting task)	These tasks measure the ability to quickly attain maximum alertness and readiness to respond following an external warning stimulus. Individuals' response speed following warning signals is compared to their response speed on trials without warning signals.	(Buchholz & Davies, 2008; Goldfarb & Shaul, 2013)
	Continuous performance tasks (CPT)	These tasks measure the ability to remain vigilant over a prolonged period. Individuals are typically presented with a continuous series of stimuli and must respond quickly and accurately only to a rarely occurring target stimulus.	(Alloway et al., 2014; Taroyan et al., 2007)
	Simple reaction time tasks (SRT)	These tasks measure the ability to maintain a general state of vigilance/alertness, processing speed, and motor speed. Individuals respond as quickly as possible to a known stimulus that is presented in a known location with the same motor response.	(Iles et al., 2000; Nicolson & Fawcett, 2000; Rüsseler et al., 2006)
	Choice reaction time tasks (CRT)	These tasks measure the ability to maintain a general state of vigilance/alertness, processing and decision response speed, and motor speed. Individuals are presented with two or more known possible stimuli, each requiring a different response. The goal is to response correctly to each presented stimulus as quickly as possible.	(Nicolson & Fawcett, 2000)
Orienting Component	Exogenous spatial cueing tasks	Individuals are presented with a spatial cue, prior to the presentation of a target stimulus, designed to automatically attract attention to the location of the cue (e.g., a brief stimulus onset in the peripheral visual field). Individuals' response speeds to targets presented in the same location of the pre-cue (i.e., valid cue condition) are compared to their response speeds to targets presented in a different location as the pre-cue (i.e., invalid cue condition).	(Buchholz & Davies, 2008; Goldfarb & Shaul, 2013; Roach & Hogben, 2004)
	Visual search tasks	Individuals are presented with a target stimulus amongst an array of distractor stimuli. There are two main types of visual search tasks: (1) feature search wherein the target is different from the distractors by a single feature (e.g., a red target amongst black distractors), and (2) conjunction search wherein the target differs from the distractors by a combination of two or more features (e.g., a red circle target amongst black circle and red square distractors). Speed and accuracy on conjunction search tasks are used as measures of goal-directed attentional orienting.	(Buchholz & McKone, 2004; Iles et al., 2000; M. W. Jones et al., 2008)

Posner's Attention Network Component	**Task**	**Task Description**	**Citation(s) mentioned in this thesis that used the task**
Executive Control (i.e., Attentional Control) Component	Response inhibition tasks (e.g., go/no-go tasks, stop signal tasks)	Stop signal tasks: Individuals are presented with a continuous series of stimuli to make responses to but must withhold a response when a stimulus is immediately followed by a stop signal. Response inhibition is typically measured by stop-signal reaction time (SSRT), an estimate of the stop-process duration, with lower SSRT representing better performance.	(Goranova, 2019)
		Go/No-Go tasks: Individuals are presented with a continuous series of target and non-target stimuli. The goal is to make a response as quickly as possible to targets (i.e., *go* trials) and without a response to non-targets (i.e., *no-go* trials). Response inhibition is typically measured by rate of commission errors/false alarms (i.e., making a response on no-*no-go* trials) with fewer errors representing better performance.	(Smith-Spark et al., 2016)
	Interference control/ conflict resolution tasks (e.g., Stroop, Simon, and Flanker tasks)	Stroop Tasks: In the classic Stroop task, Individuals must name/indicate the colour of the ink that a colour word is printed in instead of reading the world (e.g., saying "red" when the word "blue" is printed in red ink). In other words, they must inhibit a presumed automatic response (i.e., reading the word). Speed and accuracy are used as indicators of interference control/conflict resolution.	(Beidas et al., 2013; Kapoula et al., 2010; Proulx & Elmasry, 2015)
		Simon Tasks: Individuals are presented with a series of stimuli and make rightward responses (e.g., right arrow key) to one stimulus and leftward responses (e.g., left arrow key) to another stimulus. On congruent trials, the correct response to the stimulus is on the same side as the stimulus is presented on or pointing in the same direction (e.g., a right arrow key response to a stimulus presented on the right side of a visual display). On incongruent trials, the stimulus is presented on a different side than the correct response (e.g., a right arrow key response to an auditory stimulus presented to the left ear). Interference control/conflict resolution is typically measured by calculating the difference in reaction time and accuracy between congruent and incongruent trials, with longer reaction times and lower accuracy on incongruent trials than congruent trials representing worse performance.	(Gabay et al., 2020; Goranova, 2019)
		Flanker Tasks: Individuals are tasked with making one of two responses (e.g., right or left arrow key) to target stimuli while ignoring adjacent flanking stimuli. There are three types of flanker stimuli: (1) a congruent stimulus that are associated with the same response that the target stimulus is assigned (e.g., both target and flanker associated with a right arrow key	(Goldfarb & Shaul, 2013; Goranova, 2019; Mahé et al., 2014)

Posner's Attention Network Component	**Task**	**Task Description**	**Citation(s) mentioned in this thesis that used the task**
(Continued) Executive Control (i.e., Attentional Control) Component	(Continued) Interference control/ conflict resolution tasks (e.g., Stroop, Simon, and Flanker tasks)	response) , (2) an incongruent stimulus that are associated with the opposite response than the target stimulus is assigned (e.g., left arrow key response when the target is associated with a right arrow key response), and (3) a neutral stimulus with no associated response. Interference control/conflict resolution is typically measured by calculating the difference in reaction time and accuracy between trials with congruent and incongruent flankers, with longer reaction times and lower accuracy on incongruent trials than congruent trials representing worse performance.	
	Switching/ Shifting tasks	Task switching paradigms: Individuals switch between two different tasks (e.g., adding and subtracting; colour and shape discrimination tasks). Reaction time and accuracy switch costs (i.e., the difference between trials when a switch between tasks is required and when as switch is not required) are often used as measures of switching/shifting. Dual-task paradigms: Individuals are tasked with performing two tasks simultaneously. Reaction time and accuracy dual-task costs (i.e., the difference in dual task and single task performance) are often used as measures of switching/shifting.	(Smith-Spark et al., 2016; Stoet et al., 2007)

Appendix D: Description of WM tasks mentioned in the thesis

WM measure type	Task	Task Description	Examples of Version Types	Citation(s) mentioned in this thesis that used task
WM maintenance	Simple span	Forward Span: Participants recall a series of presented stimuli in forward serial order. Only maintenance of WM functions involved. Backwards Span: Participants recall a series of presented stimuli in backwards serial order. Both maintenance and executive WM functions involved. Letter-Number Sequencing: Participants are presented with a mixed sequence of letters and numbers, one at a time, and recall the series with the numbers in numerical order followed by the letters in alphabetical order. Both maintenance and executive WM functions involved.	Auditory stimuli: Numbers, Words, Letters Visual stimuli: Spatial Locations, Pictures	(Artuso et al., 2019; Byrne et al., 2019; Chacko et al., 2014; K. I. E. Dahlin, 2011; Dunning et al., 2013; Egeland et al., 2013; Engle et al., 1999; Fälth et al., 2015; Ghani & Gathercole, 2013; Gray et al., 2012; Gropper et al., 2014; Holmes et al., 2009; J. S. Jones et al., 2020; Pahor et al., 2021; Partanen et al., 2015; Sánchez-Pérez et al., 2018; Shiran & Breznitz, 2011; Söderqvist & Nutley, 2017)
	Sternberg task	Participants are visually presented with a to be remembered series of stimuli, one at a time (i.e., a memory set). Followed by the presentation of the memory set, they are presented with a probe item and must indicate whether the item was in the memory set or not.	Verbal stimuli: Numbers Visual stimuli: Spatial locations, Pictures	(Horowitz-Kraus & Breznitz, 2009; Matysiak et al., 2019; Sánchez-Pérez et al., 2018)

WM measure type	**Task**	**Task Description**	**Examples of Version Types**	**Citation(s) mentioned in this thesis that used task**
WM executive	Complex span	Participants engage in a memory task and a secondary processing task. Typically, to be serially recalled/recognized items (e.g., numbers, spatial locations) are presented, one at a time, in between trials of the secondary processing task (e.g., math operations, symmetry judgments).	Operation span – Memory task: serial recall of unrelated words or numbers; Processing task: math operation judgment Reading span (version 1; Engle et al., 1999) – Memory task: serial recall of the last words of, or printed immediately following, the sentences in processing task; Processing task: judge whether a written sentence is plausible or not Reading span (version 2; Kane et al., 2004) – Memory task: serial recognition of letters; Processing task: judge whether a sentence makes sense or not Listening span – Memory task: serial recall of the last words of the sentences in the processing task; Processing task: judge whether an auditorily presented sentence is plausible or not Sentence span – Memory task: Serial recall of the words generated in the processing task; Processing task: generate the last word of and auditorily presented sentence Computation span – Memory task: serial recall of the last digits of the processing task; Processing task: solve math problems Counting span – Memory task: serial recall of the number of tallied stimuli on each trial of the processing task; Processing task: count the number of a visual stimulus presented amongst distractors. In some versions, also make odd/event judgement Rotation span – Memory task: serial recognition if the direction and lengths of arrows; Processing task: judge whether a rotated letter is regular or mirrored Symmetry span – Memory task: spatial location of square in a 4x4 matrix; Processing task: symmetry judgement of 8x8 matrix	(Chein & Morrison, 2010; Chooi & Logie, 2020; Clouter, 2013; Engle, Tuholski, et al., 1999, 1999; Ghani & Gathercole, 2013; Guye et al., 2017; Henry et al., 2014; Lawlor-Savage & Goghari, 2016; Loosli et al., 2012; Matysiak et al., 2019; Pahor et al., 2021; Redick et al., 2020; Schmiedek et al., 2014; Smith-Spark et al., 2016; Smith-Spark & Fisk, 2007; Wiemers et al., 2019; Wilhelm et al., 2013)

WM measure type	**Task**	**Task Description**	**Examples of Version Types**	**Citation(s) mentioned in this thesis that used task**
(Continued) WM executive	*N*-back	Participants are presented with a series of auditory (e.g., words or letters) and/or visuospatial stimuli and indicate stimulus matches occurring “n” trials before. For instance, on an n-level of two, participants must indicate whether the current stimulus or stimuli matched the one(s) from two trials back. *N*-back tasks may be single (i.e., only one stimulus type, one at a time) or dual (i.e., two stimulus types presented simultaneously).	Auditory stimuli: Numbers, Letters, Words, Visual stimuli: Spatial Locations, Pictures	(Assecondi et al., 2021; Au et al., 2015; Brose et al., 2012; Bürki et al., 2014; Byrne et al., 2019; Chooi & Logie, 2020; Clouter, 2013; Fellman et al., 2020; Jaeggi et al., 2010, 2014; Küper & Karbach, 2016; Laine et al., 2018; Maraver et al., 2016; Ørskov et al., 2021; Ploughman et al., 2019; Redick et al., 2013, 2013; Rhodes & Katz, 2017; Salmi et al., 2020; Salminen et al., 2012; Sánchez-Pérez et al., 2018; Schmiedek et al., 2014; Soveri et al., 2017; Thompson et al., 2013; Wilhelm et al., 2013).
	Running-memory span	Participants are presented with series of items of varying unknown lengths and must recall the last *n* number of items.	Verbal stimuli: Numbers, Words Visual stimuli: Spatial locations	(Artuso et al., 2019; Laine et al., 2018; Redick et al., 2020; Wiemers et al., 2019)

Appendix E: Summary of Training Studies With Reading Outcomes in Child Samples

Sample Characteristic: Attention Deficits, WM Deficits, and/or Learning Difficulties

Study	Sample	Training Program	Control	Dose	Reading Outcome	Reading Category	Effect size (*d*)	Follow -up Effect size (*d*)	Follow -up Time
Holmes et al., (2009)	English speaking children with low WM (i.e., at or below the 15th percentile on both the verbal test and backward digit recall from the AWMA); *n*=42 Age: 8-11; Training: *M* = 10y 1m; Control: *M*=9y 9m	Cogmed *n*=22	Active (non-adaptive Cogmed) *n*=20	11.67-14.6	Word reading (WORD/ WIAT)	Decoding	0.01	0.07 (no control)	6 mo.
K. I. E. Dahlin, (2011)	Swedish speaking children with special education needs in grades 3-5 with attention problems; n=57 Age: 9-12; *M(SD)*=unknown	Cogmed *n*=42	Passive (*n=15)*	12.5-16.67 hours	Reading Comprehension (PIRLS)	Passage comprehension	0.88**	0.91*	6-7 mo.
					Phonological non-word reading test	Decoding	0.37	0.17	6-7 mo.
Gray et al. (2012)	English speaking children coexisting LD/ADHD plus severe problems in learning and behavior. Previously found to be intervention resistant Age: 12-17; *M(SD)*=14.3(1.2)	Cogmed *n*=32	Math training program *n*=20	15-18.75 hours	Word reading (WRAT4)	Decoding	-0.02		
					Sentence comprehension (WRAT4)	Sentence comprehension	0.05		

Study	**Sample**	**Training Program**	**Control**	**Dose**	**Reading Outcome**	**Reading Category**	**Effect size (*d*)**	**Follow-up Effect size (*d*)**	**Follow-up Time**
Dunning et al. (2013)	English speaking children with low WM (i.e., at or below the 15th centile on both the verbal test and backward digit recall from the AWMA); *n*=94 Age: 7-9; *M(SD)=8y*5m(7.97m)	Cogmed *n*=34 (*n*=15 @ 12 mo. follow-up)	Active (non-adaptive Cogmed) *n*=30 (*n*=18 @ 12 mo. follow-up) Passive *n*= 30	10-18.75 hours	Word reading (WORD)	Decoding	0.36	0.14	12 mo.
					Reading ability (NARA)	Passage comprehension	0.40	0.0	12 mo.
						Reading accuracy	0.03	-0.22	12 mo.
						Reading rate	0.04	-0.66	12 mo.
Egeland et al. (2013)	Children in Norway with confirmed diagnosis of F-90 ICD-10 Hyperkinetic Disorder equivalent to DSM-IV ADHD combined type *n*=67 Age: 10-12; *M(SD)*=10.4(0.7)	Cogmed *n*=33	Passive *n*=34	12.5-18.75 hours	Quality of Decoding (LOGOS)	Decoding	0.57*	0.64*	8 mo.
					Word Decoding Speed (LOGOS)	Speed of decoding	-0.32	-0.15	8 mo.
					Reading Fluency, Accuracy (LOGOS)	Passage comprehension and fluency	0.46*	0.62*	8 mo.
					Reading Fluency, Time (LOGOS)	Reading rate	0.42*	0.17*	8 mo.
Chacko et al., (2014)	English speaking children with ADHD *n*=85 Age: 7-11 Training: *M*(SD)=8.4(1.4) Control*: M*(SD)=8.4(1.3)	Cogmed *n=44*	Active (non-adaptive Cogmed) *n=41*	12.5-18.75 hours	Word reading (WRAT4)	Decoding	-0.05		
					Sentence comprehension (WRAT4)	Sentence comprehension	0.31		

Study	**Sample**	**Training Program**	**Control**	**Dose**	**Reading Outcome**	**Reading Category**	**Effect size (*d*)**	**Follow-up Effect size (*d*)**	**Follow-up Time**
Partanen et al. (2015)	Swedish speaking children with special education needs (SEN) based on need for support in planning, attention, and/or WM SEN group did not have clinically low WM performance Age: 8-9 Training: *M*(SD)=8.61(.51) Control: *M*(SD)=8.41(.57)	Cogmed *n*=20	Passive *n*=24	15-18.75 hours	Diagnostics of reading and writing abilities (Swedish DLS)	Passage comprehension	-0.15	0.07	6 mo.

Sample Characteristic: Typically Developing

Study	**Sample**	**Training Program**	**Control**	**Dose**	**Reading Outcome**	**Reading Category**	**Effect size (*d*)**	**Follow-up Effect size (*d*)**	**Follow-up Time**
Loosli et al. (2012)	Typically developing German-speaking children in Switzerland *n*=40 Age: 9-11; *M(SD)*=9.5(0.56)	Adaptive visual complex span *n*=20	Passive *n*=20	2 hours	Reading ability (Salzburger Lesetest)	Decoding	0.72*		
						Decoding	< 0.18		
						Passage comprehension	1.03**		
Henry et al. (2014)	Typically developing English-speaking children *n*=36 Age: 5-8; *M(SD)*=84mo.(12.94)	Adaptive Listening Recall and of Odd One Out tasks *n*=18	Active (Versions of the training tasks with no requirement for memory storage) *n*=18	3 hours	Word Reading (BAS-II)	Decoding	0.09	0.15 0.10	6 mo. 12 mo.
					Reading Comprehension (WORD) ONLY GIVEN @ 12m	Passage comprehension		0.97**	12 mo. (only group comparison)

Study	**Sample**	**Training Program**	**Control**	**Dose**	**Reading Outcome**	**Reading Category**	**Effect size (*d*)**	**Follow -up Effect size (*d*)**	**Follow -up Time**
Fälth et al. (2015)	Typically developing children (possibly in Sweden); *n*=32 Age: 7; *M(SD)*=not reported	Cogmed *n*=16	Passive *n*=16	18.75 hours	'Words and Image'	Decoding	1.09	1.24	8 weeks
Karbach et al. (2015)	Native German-speaking elementary school children *n*=28 Age: 7y2m-9y7m; *M(SD)*=8y4m(0.07)	Braintwis-ter *n*=14	Active (non-adaptive Braintwister) *n*=14	9.33 hours	Knuspels Reading Tasks	Reading composite consisting of Sentence comprehension (auditory and silent reading) and decoding	2.52*	2.06*	3 mo.
Söderqvist and Nutley (2017)	Elementary school children in Sweden. Of total sample, 4 with dyslexia/dyscalculia and 3 with ADHD/ADD *n*=61 Age: 10-11; Training: *M(SD)*=9.85(0.32) Control: *M(SD)*=9.77(0.30)	Cogmed *n*=20	Passive *n*=22	~7.5 to 9.20 hours	Diagnostics of reading and writing abilities (DLS)	Composite of Passage comprehension reading rate, and spelling		0.66*	24 mo.

Study	**Sample**	**Training Program**	**Control**	**Dose**	**Reading Outcome**	**Reading Category**	**Effect size (*d*)**	**Follow-up Effect size (*d*)**	**Follow-up Time**
Sánchez-Pérez et al. (2018)	Typically developing Spanish monolingual children *n*=104 <u>Age</u>: 7-12; *M(SD)*=9.17(1.20)	WM + math training (three WM training tasks: *n*-back, abstract shapes, WM span) *n*=51	Passive *n*=53	13 hours	Reading ability (PROLEC-R)	Reading composite consisting of measures of identification of letters, syntactic processes, and decoding	0.33**		
Artuso et al. (2019)	Typically developing Italian-speaking children *n*=62 <u>Age</u>: 9-10; WM Training: *M(SD)*=9.42(0.41) Metacognitive training: *M(SD)*=9.35(0.33) Active Control: *M(SD)=9.74(0.26)*	WM updating (WMU) tasks *n*=27	Active (Reading comprehension practice w/o instruction) *n*=19 Metacognitive training *n*=26	6.67 hours	Reading comprehension (Prove MT-kit scuola primaria)	Passage comprehension	1.04** WMU vs. ActiveC 0.51* WMU vs. Metacog.		
J. S. Jones et al. (2020)	Typically developing English-speaking children *n*=95 <u>Age</u>: 9-14; *M(SD)*=12.51(1.18)	Cogmed *n*=23 Cogmed + Metacognitive workbook *n*=26	Active (Adaptive visual search task) *n*=28	20-25 hours	Reading Comprehension (WIAT-II)	Passage comprehension	Null	Null	3 mo.

Appendix F: Summary of Training Studies With Reading Outcomes in Adult Samples

Sample Characteristic: Impaired Readers

Study	**Sample**	**Training Program**	**Control**	**Dose**	**Reading Outcome**	**Reading Category**	**Effect in training groups**	**Effect in control groups**
Shiran and Breznitz (2011)	Hebrew-speaking University students: with impaired readers (*n*=41) and skilled readers (*n*=50) <u>Age</u>: Impaired readers: *M*(SD)=24.84(2.89) Skilled readers: *M(SD)*=25.11(1.97)	CogniFit Personal Coach	Active (Self-paced reading training w/o instruction (read 50 sentences per session, each followed by one multiple choice reading comprehension question)	6 hours	Words per minute	Decoding	Main effect of training ***	No main effect of training
					Pseudowords per minute	Decoding	Main effect of training ***	No main effect of training
					Silent reading comprehension in context	Reading Comprehension (unclear if passage or sentence)	Main effect of training ***	No main effect of training
					Silent reading time	Reading rate	Main effect of training **	No main effect of training

Sample Characteristic: ADHD and/or LD

Study	**Sample**	**Training Program**	**Control**	**Dose**	**Reading Outcome**	**Reading Category**	**Effect size (*d*)**	**Follow-up Effect size (*d*)**	**Follow-up Time**
Gropper et al. (2014)	University and College students in Canada with ADHD, LD, or both; *n*=43 <u>Age</u>: 19-52; *M(SD)*=28.04 (7.2)	Cogmed *n*=24	Passive *n*=21	18.75 hours	Reading Comprehension (Nelson-Denny)	Passage comprehension	-0.14	-0.48	3 mo.

Sample Characteristic: Typically Developing

Study	Sample	Training Program	Control	Dose	Reading Outcome	Reading Category	Effect size (*d*)	Follow-up Effect size (*d*)	Follow-up Time
Chein and Morrison (2010)	General sample of English-speaking undergraduate students; *n*=42 Age: Training: *M*=20.1 Control: *M*=20.6	Adaptive letter and spatial complex span *n*=20	Passive *n*=22	10-15 hours	Reading Comprehension (Nelson-Denny)	Passage comprehension	0.58*		
Thompson et al. (2013)	General sample of English-speaking adults *n*=58 Age: 18-45 criteria; Training: *M*=21.2 Active Control: *M*=21.3 Passive Control: *M*=23.1	Adaptive dual *n*-back training *n*=20	Active (adaptive multiple object tracking (MOT)) *n*=19 Passive *n*=19	8.33 hours	Reading Comprehension (Nelson-Denny)	Passage comprehension	0 Training group started @ grade equiv. >17.1		
					Reading Rate (Nelson-Denny)	Reading rate	-0.04 (Active) 0.25 (Passive)		
Redick et al. (2020)	Community sample of native English speaking adults *n*=86 Age: 18-30; O-L: *M(SD)*=20.53(1.17) O Mix: *M(SD)*=20.41(2.41) Control: *M(SD)*=20.59(2.43)	Adaptive Operation-Letter (O-L) n=30 Adaptive Operation Mix (O Mix) *n*=27	Active (visual search task) *n*=29	5 hours	Reading Comprehension (Nelson-Denny) excluding first passage	Passage comprehension	0.19 (O-L vs. Control) 0.34 (O Mix vs. Control)		

Appendix G: Screening and Background Questionnaire

Participant #:_________________ Date:___________________

Email address:
Phone number:
Month and year of birth:
Age:

Gender:
Writing hand:
Year in University:
Program in University:

First Language:

1. In which language did you first learn to speak (e.g. English, French, Arabic, Chinese)? ____________
2. In which language did you first learn to read and write? (e.g. English, French [francophone school), French [immersion program], Arabic, Chinese)? ___________

What is your general state of health? Excellent Very Good Good Fair Poor

Have you ever been diagnosed or treated for a head injury with loss of consciousness? If so, how long were you unconscious for?

Do you have any neurological problems (e.g., MS, Seizures, movement disorder)?

Do you have any psychiatric problems (e.g., a diagnosis of depression, anxiety disorder)?

Do you have an injury or condition that limits your use of your dominant hand (e.g., sprain, arthritis)?

Do you have any diagnosed learning disabilities (e.g. attention deficit disorders, dyslexia)? If so, what was the diagnosis and when did you receive the diagnosis (elementary school, middle school, high school, university, don't recall)?

Have you ever repeated a grade?

<u>Medications:</u>
Please list any medication you are taking:

Have you started on a new medication or changed the dose of one of your medications in the past 4 weeks? If so, which medication(s)?

Appendix H: Test List Order

Test Name	Study 1	Study 2
DalCAB	Yes (all eight subtests)	Yes (Item Memory and Location Memory subtests)
TOWRE SWE[a]	Yes	Yes
TOWRE PDE[a]	Yes	Yes
NDRT-RC[a]	Yes	Yes
LASSI-Conc	Yes	Yes
Operation Span[a]	Yes	Yes
Symmetry Span	Yes	Yes
SESRS	No	Yes[b]
ASE	No	Yes[b]
Reading Span	No	Yes

Note: Assessment measures were administered in the order that they are listed; a-Test List A: Form A of the TOWRE, Form G of the NDRT-RC, and version 1 of the Operation Span task; Test List B: Form B of the TOWRE, Form H of the NDRT-RC, and version 2 of the Operation Span; b-the data from these measures was collected to address another research question not reported in this dissertation.

Appendix I: Follow-Up Fixed Order Regression Results with Group, Attention Measures, and WM Measures as Predictors, and Decoding as the Outcome

Model	Step	Predictor	Outcome: Decoding Composite	
			β	R^2
Model 1:	1	Group	-.36***	.13***
Attention[2]	2	Vigilance: Processing Speed Composite	.08	
		Vigilance: Decision Speed Composite	-.35***	
		Orienting Composite	.08	
		AC: Switch/Shifting Composite	.01	
		AC: Interference Control/Conflict Resolution Composite	-.16 ^{t}	
		AC: Response Inhibition Composite	-.12	
				.13*
	3	Group x Vigilance: Decision Speed Composite	.14	.02
Model 2:	1	Group	-.31***	.13***
WM	2	Item Memory %Error	-.26*	
Maintenance[3]		Location Memory %Error	-.09	
				.08**
	3	Group x Item Memory %Error	-.10	
		Group x Location Memory %Error	-.23*	
				.04 ^{t}
Model 3:	1	Group	-.17 ^{t}	.13***
WM	2	Operation Span Total	.45***	
Executive[4]		Symmetry Span Total	.03	
				.16***
	3	Group x Operation Span Total	-.08	.01

Note: The standardized beta coefficients are from the final step of the regression model; AC=Attentional Control; WM=Working Memory; $^{t}\, p < .10$, $^{*}\, p < .05$, $^{**}\, p < .01$, $^{***}\, p < .001$.

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[2] These results are different from our findings from the multiple regressions conducted separately for HRD and NRD. There was no Group x Vigilance: Decision Speed interaction; instead, faster vigilance decision speed was associated with better decoding performance in both groups.

[3] The significant Group x Location Memory % Error interaction is consistent with our findings from the multiple regressions conducted separately for HRD and NRD; better accuracy on the Location Memory task was associated with better decoding performance only in the HRD group. Different from our findings from the separate HRD and NRD multiple regression models, the Group x Item Memory % Error interaction was not significant; instead, greater accuracy on the Item Memory task was associated with better decoding performance in both groups.

[4] These results are consistent with our findings from the separate group multiple regressions. Better Operation Span performance was associated with better decoding performance in both HRD and NRD.

Appendix J: Follow-Up Fixed Order Regression Results with Group and WM Measures as Predictors, and Reading Comprehension as the Outcome

Model	Step	Predictor	Outcome: NDRT Reading Comprehension %Correct	
			β	R^2
Model 1: WM Maintenance[5]	1	Group	-.28**	
		Decoding Composite	.26*	
				.24***
	2	Item Memory %Error	-.12	
		Location Memory %Error	-.31**	
				.07**
	3	Group x Decoding Composite	-.01	
		Group x Location Memory %Error	-.15 ^{t}	
				.02
Model 3: WM Executive[6]	1	Group	-.16 ^{t}	
		Decoding Composite	.11	
				.24***
	2	Operation Span Total	.47***	
		Symmetry Span Total	-.02	
				.13***
	3	Group x Decoding Composite	-.10	
		Group x Operation Span Total %Error	-.02	
				.01

Note: The standardized beta coefficients are from the final step of the regression model; AC=Attentional Control; WM=Working Memory; ^{t} $p < .10$ * $p < .05$, ** $p < .01$, *** $p < .001$.

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[5] The trend (i.e., $p = .09$) interaction between Group and Location Memory % Error is consistent with our findings from the multiple regressions conducted separately for HRD and NRD; better accuracy on the Location Memory task was associated with better reading comprehension only in the HRD group. Contrary to our findings from the separate HRD and NRD regression analyses, there was no Group x Decoding Composite interaction; instead, better decoding performance was associated with better reading comprehension performance in both groups.

[6] These results are consistent with our findings from the multiple regressions conducted separately for HRD and NRD. Better Operation Span performance was associated with better decoding performance in both groups. Contrary to our findings from the separate HRD and NRD regression analyses, there was no Group x Decoding Composite interaction; instead, better decoding performance was associated with better reading comprehension performance in both groups.

Appendix K: Dalhousie Computerized Attention Battery Task Descriptions

Task	Task Description	Task-Related Variables
Simple Reaction Time (SRT)	Respond as quickly as possible to the onset of a stimulus.	Response-stimulus intervals (three RSIs between 500ms and 1500ms)
Go/No-Go (GNG)	Respond (go) or inhibit response (no-go) to specified targets	Go Frequency (20% and 80%)
Choice Reaction Time (CRT)	Respond with one of potential responses, depending upon the target.	Trial type (Switch = different response required than previous trial; No-switch = same response required as previous trial)
Dual Task (DT)	Two tasks completed at the same time: (1) CRT (see above); (2) counting task that requires keeping track of both targets' frequencies	CRT Trial type (switch and no-switch); Counting set size (eight and 12)
Vertical Flanker	Two-choice identification task with flanking distractors; congruent or incongruent with target in the centre	Flanker Congruency (congruent and incongruent)
Item Memory (IM)	Modified Sternberg task (Sternberg, 1966) wherein participants identify whether a single probe stimulus was present in a set of items shown right before	Set size (three set sizes between two and six); Trial type (target present and target absent)
Location Memory (LM)	Modified Sternberg task (Sternberg, 1966) wherein participants identify whether the location of a single probe stimulus was present in a set of items shown right before	Set size (three set sizes between two and six); Trial type (target present and target absent)
Visual Search	Locate and indicate orientation of target (i.e., upright or inverted) among distractors that do or do not share features with the target (conjunction or feature search, respectively)	Search type (feature or conjunction) Set size (three set sizes between five and 17)

Appendix L: Scheduled Changes to the Training Activity

Training Session	Number of Trials	Range of interstimulus intervals (seconds)	Visual Stimuli	Audio Stimuli
1-5	20+n[a]	2.5-3.5	Triangles [8 stimuli options] (20 blocks of 20 dual modality trials)	Phonologically Distinct Letters [QFBRXMKH]
6-10	25+n[a]	2-3	Pictures of lighthouse [location of lighthouse changes] (20 blocks of 25 dual modality trials)	Phonetic Alphabet [Alpha, Bravo, Charlie, Delta, Echo, Foxtrot, Golf, Hotel]
11-15 [b]	30+n[a]	1.5-2.5	Landscape pictures (20 blocks of 30 dual modality trials)	Words [Case, Fact, Health, Life, Need, Part, Thought, Work]

Note: a- for the WM training group, the total number of trials consisted of the set number plus the number of window/speakers present; b– All participants, apart from one, were instructed to complete 10 training sessions over the course of three weeks. One participant completed 15 training sessions over the course of the 3-week period, prior to changes made to the study methodology.

Appendix M: Pre-Training Expectation Questionnaire

Part#:________ Date: _________________

Expectations Questions (Session 1):

On a scale of 1 to 5, please indicate how much you think that the 3-weeks of your activity will improve your performance on the following tests:

1. The computer task where you remember a series of playing cards and determine if a subsequently presented card was present in the series.

   |—————|—————|—————|—————|
   1 2 3 4 5
   (not at all) (unsure) (very much)

2. The computer task where you remember the location of a series of playing cards and determine if a subsequently presented card location was one of the locations presented in the series.

   |—————|—————|—————|—————|
   1 2 3 4 5
   (not at all) (unsure) (very much)

3. The single word speed reading task

   |—————|—————|—————|—————|
   1 2 3 4 5
   (not at all) (unsure) (very much)

4. The made-up word speed reading task

   |—————|—————|—————|—————|
   1 2 3 4 5
   (not at all) (unsure) (very much)

5. The passage-reading comprehension task.

   |—————|—————|—————|—————|
   1 2 3 4 5
   (not at all) (unsure) (very much)

6. The computer task where you do both mathematical equations and remember words.

   |—————|—————|—————|—————|
   1 2 3 4 5
   (not at all) (unsure) (very much)

7. The computer task where you judge matrix symmetry and remember red square locations.

|——————|——————|——————|——————|
1 2 3 4 5
(not at all) (unsure) (very much)

8. The computer task where you read sentences and remember letters.

|——————|——————|——————|——————|
1 2 3 4 5
(not at all) (unsure) (very much)

On a scale of 1 to 5, please indicate how much you think that the 3-weeks of your activity will help you to:

9. Concentrate during school activities (e.g., studying, in class, doing school work).

|——————|——————|——————|——————|
1 2 3 4 5
(not at all) (unsure) (very much)

10. Concentrate while reading.

|——————|——————|——————|——————|
1 2 3 4 5
(not at all) (unsure) (very much)

11. Use concentration strategies while reading.

|——————|——————|——————|——————|
1 2 3 4 5
(not at all) (unsure) (very much)

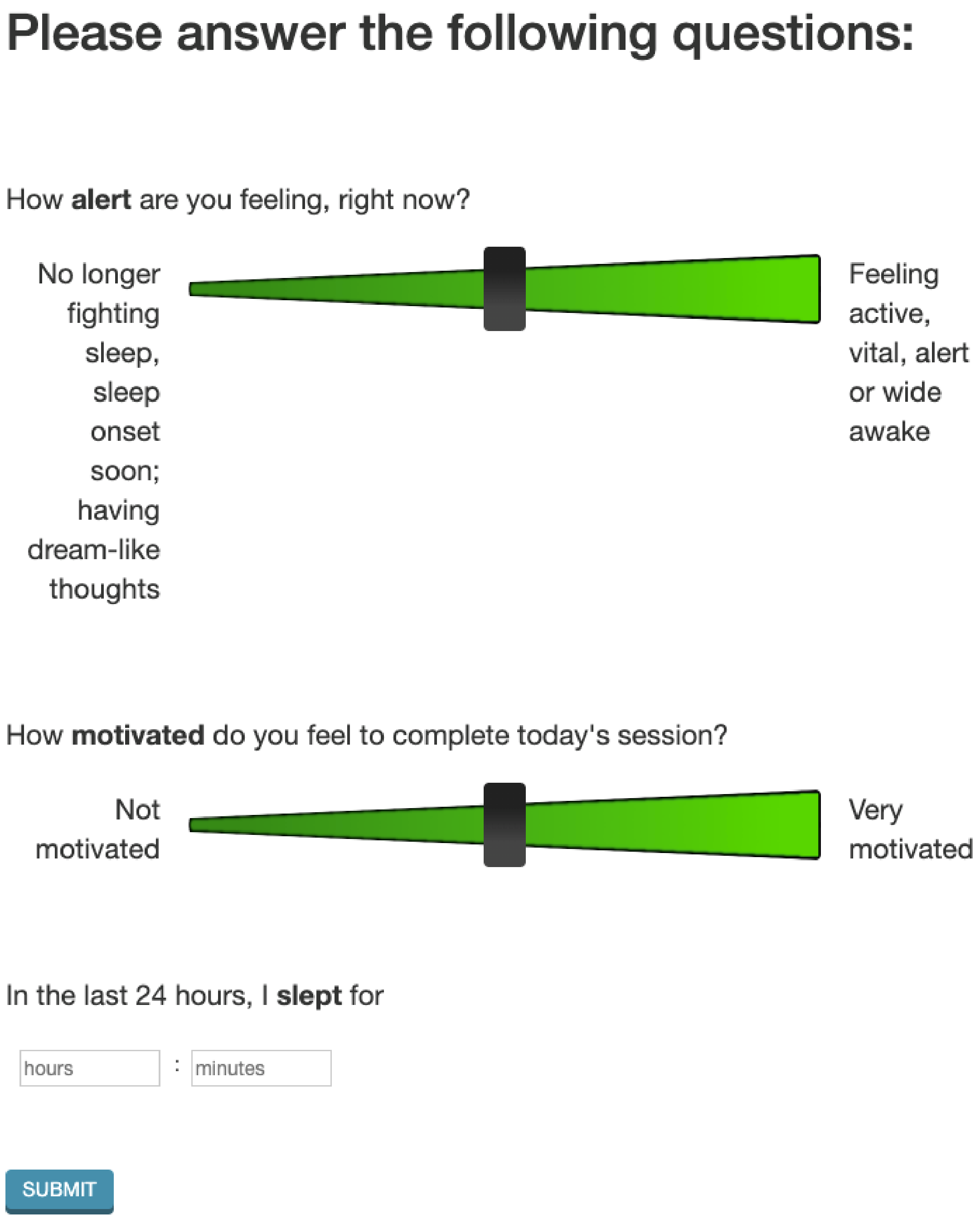
12. Use strategies to do well in school.

|——————|——————|——————|——————|
1 2 3 4 5
(not at all) (unsure) (very much)

13. Feel more confident about your ability to understand class materials and do well on academic tasks.

|——————|——————|——————|——————|
1 2 3 4 5
(not at all) (unsure) (very much)

Appendix N: Pre-training Activity Questions



Please answer the following questions:

How **alert** are you feeling, right now?

No longer fighting sleep, sleep onset soon; having dream-like thoughts

Feeling active, vital, alert or wide awake

How **motivated** do you feel to complete today's session?

Not motivated

Very motivated

In the last 24 hours, I **slept** for

Appendix O: Post-Training Expectation Questionnaire

Part#:________ Date: _________________

Expectations Questions (Session 2):

On a scale of 1 to 5, please indicate how much you think that the 3-weeks of your activity has improved your performance on the following tests:

1. The computer task where you remember a series of playing cards and determine if a subsequently presented card was present in the series.

|————|————|————|————|
1 2 3 4 5
(not at all) (unsure) (very much)

2. The computer task where you remember the location of a series of playing cards and determine if a subsequently presented card location was one of the locations presented in the series.

|————|————|————|————|
1 2 3 4 5
(not at all) (unsure) (very much)

3. The single word speed reading task

|————|————|————|————|
1 2 3 4 5
(not at all) (unsure) (very much)

4. The made-up word speed reading task

|————|————|————|————|
1 2 3 4 5
(not at all) (unsure) (very much)

5. The passage-reading comprehension task.

|————|————|————|————|
1 2 3 4 5
(not at all) (unsure) (very much)

6. The computer task where you do both mathematical equations and remember words.

|————|————|————|————|
1 2 3 4 5
(not at all) (unsure) (very much)

7. The computer task where you judge matrix symmetry and remember red square locations.

1	2	3	4	5
(not at all)		(unsure)		(very much)

8. The computer task where you read sentences and remember letters.

1	2	3	4	5
(not at all)		(unsure)		(very much)

On a scale of 1 to 5, please indicate how much you think that the 3-weeks of your activity has helped you to:

9. Concentrate during school activities (e.g., studying, in class, doing school work).

1	2	3	4	5
(not at all)		(unsure)		(very much)

10. Concentrate while reading.

1	2	3	4	5
(not at all)		(unsure)		(very much)

11. Use concentration strategies while reading.

1	2	3	4	5
(not at all)		(unsure)		(very much)

12. Use strategies to do well in school.

1	2	3	4	5
(not at all)		(unsure)		(very much)

13. Feel more confident about your ability to understand class materials and do well on academic tasks.

1	2	3	4	5
(not at all)		(unsure)		(very much)

Appendix P: Bivariate Correlations Between Study 1 Participant Characteristics, Attention and Working Memory Predictors, and Reading Outcomes Across Sample of HRD and NRD Students (*n* = 102)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Age															
2	Education years	.78***														
3	TOWRE SWE	-.09	.04													
4	TOWRE PDE	-.14	.02	.69***												
5	Decoding Comp.	-.12	.03	.94***	.90***											
6	NDRT-RC %Correct	.06	.23	.13	.39**	.27										
7	Vigilance: Proc.	-.02	-.11	-.06	-.03	-.05	-.07									
8	Vigilance: Decision Speed Comp	.08	-.03	-.46***	-.34*	-.44**	.01	.48***								
9	Orienting Comp.	-.02	.002	.11	.11	.12	.05	.12	.14							
10	AC: Switching/	.14	.16	.01	-.02	-.004	-.01	.17	.21	.13						
11	AC: Interference Control/ Conflict	.09	.01	.08	-.02	.04	.05	-.27	-.32*	-.17	-.30*					
12	AC: Response Inhibiting Comp.	.02	.02	-.01	-.01	-.01	.16	-.15	-.07	-.16	-.13	.02				
13	IM %Error	-.06	-.10	-.38**	-.22	-.33*	-.09	-.08	.36**	.21	-.27	-.02	-.14			
14	LM %Error	.01	-.08	-.14	-.001	-.08	-.14	.17	.21	.26	-.16	-.10	-.22	.59***		
15	OSpan Total	-.08	.05	.45***	.52***	.52***	.51***	-.08	-.35*	.03	.05	.02	.15	-.28*	-.08	
16	SymSpan Total	.04	.07	.15	.14	.16	.29*	-.33*	-.40**	-.22	-.03	.18	.20	-.27	-.10	.38**

Note: NRD = No History of Reading Difficulties; HRD = History of Reading Difficulties; Comp. = Composite; Decoding Comp. = TOWRE SWE + TOWRE PDE; IM = Item Memory; LM = Location Memory; OSpan = Operation Span; SymSpan = Symmetry Span; * $p < .05$, ** $p < .01$, *** $p < .001$.

Appendix Q: Bivariate Correlations Between Study 1 Participant Characteristics, Attention and Working Memory Predictors, and Reading Outcomes in NRD students (Above Diagonal; *n* = 51) and HRD Students (Below Diagonal; *n* = 51)

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Age		.78***	-.09	-.14	-.12	.06	-.02	.08	-.02	.14	0.09	.02	-.06	.01	-.08	.04
2	Education years	.78***		.04	.02	.03	.23	-.11	-.03	.00	.16	.01	.02	-.10	-.08	.05	.07
3	TOWRE SWE	.05	.11		.69***	.94***	.13	-.06	-.48***	.11	.01	.08	-.01	.38**	-.14	.45***	.15
4	TOWRE PDE	.18	.17	.69***		.90***	.39**	-.03	-.34*	.11	-.02	-.02	-.01	-.22	.00	.52***	.14
5	Decoding Comp.	.13	.15	.91***	.93***		.27	-.05	-.44**	.12	.00	.04	-.01	-.33*	-.08	.52***	.16
6	NDRT-RC %Correct	.04	.15	.36**	.30*	.36**		-.07	.01	.05	-.01	.05	.16	-.09	-.14	.51***	.29*
7	Vigilance: Proc. Speed Comp.	-.78	-.10	-.09	-.01	-.05	-.02		.48***	.12	.17	-.27	-.15	-.08	.17	-.08	-.33*
8	Vigilance: Decision Speed Comp	-.07	-.20	-.16	-.15	-.17	-.07	.36**		.14	.21	-.32*	-.07	.36**	.21	-.35*	-.40**
9	Orienting Comp.	.13	-.07	.01	-.07	-.03	.08	-.08	.36**		.13	-.17	-.16	.21	.26	.03	-.22
10	AC: Switching/ Shifting Comp.	-.19	-.15	-.05	.08	.02	-.04	.12	.04	-.07		-.30*	-.13	-.27	-.16	.05	-.03
11	AC: Interference Control/ Conflict Resolution Comp.	-.09	.04	-.31*	-.24	-.30*	-.24	31*	.18	.01	-.07		.02	-.02	-.10	.02	.19
12	AC: Response Inhibiting Comp.	-.09	-.12	-.16	-.29*	-.25	-.08	-.20	-.11	.01	-.04	.30*		-.14	-.22	.15	.20
13	IM %Error	-.13	-.11	-.24	-.27	-.28*	-.10	.03	.35*	-.15	.32*	.15	.12		.59***	-.28*	-.27
14	LM %Error	-.05	-.07	-.31*	-.38**	-.38**	-.47***	-.04	.32*	-.02	.01	.15	.31*	.39**		-.08	-.10
15	OSpan Total	-.02	.06	.34*	.35*	.38**	.50***	-.06	-.32*	-.01	-.09	-.26	-.10	-.32*	-.43**		.38**
16	SymSpan Total	-.01	.04	.22	.28	.27	.18	.10	-.33*	-.28*	-.11	-.03	-.03	-.23	-.38**	.52***	

Note: NRD = No History of Reading Difficulties; HRD = History of Reading Difficulties; Comp. = Composite; Decoding Comp. = TOWRE SWE + TOWRE PDE; IM = Item Memory; LM = Location Memory; OSpan = Operation Span; SymSpan = Symmetry Span; ** $p < .01$, *** $p < .001$.