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Visuospatial Learning Differences: A Study of Children and Adults With and Without Dyslexia

Author
Trebeau Crogman, Maryam

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Visuospatial Learning Differences:
A Study of Children and Adults With and Without Dyslexia

A dissertation submitted in partial satisfaction of the requirements
for the degree Doctor of Philosophy

in

Developmental Psychology

By

Maryam Trebeau Crogman

Committee in charge:

Professor Jeffrey Gilger
Professor Heather Bortfeld
Professor Jitske Tiemensma

2018

Author Note
Maryam T. Crogman, Psychological Sciences, University of California, Merced.
Correspondence concerning this article should be addressed to Maryam T. Crogman, Psychological Sciences, University of California at Merced, 5200 N. Lake Road,
Merced, CA 95343.
E-mail: mtrebeaucrogman@ucmerced.edu

The Dissertation of Maryam Trebeau Crogman is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Dr. Jitske Tiemensma

Dr. Heather Bortfeld

Dr. Jeffrey Gilger Chair

University of California, Merced

2018

I dedicate this work to my husband, Horace Crogman.
Thank you my Love, for seeing me through graduate school, for your untiring support and motivation, and your priceless academic, spiritual, and life inspiration.
I would not have done it without you.

~~~

Thank you to my mentor and friend Dr. Gilger,
for your patience and kindness on my long journey, and for your guidance in focusing my professional direction.

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~~~

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for your motivation in pushing us both to have productive summers,
and for your smile and your care that kept me going.
Your Memory lives on. ♥

"Let’s not play these kids cheap; let’s find out what they have.
What do they have that is a strength?
What do they have that you can approach and build a bridge upon?
Education is all a matter of building bridges…”

Ralph Ellison “What These Children Are Like” Lecture, 1963

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LIST OF SYMBOLS

Symbols	**Meaning**
*	Symbol indicating statistical significance at the .05 level
**	Statistically significant at the .01 level
†	Approaching significance .06
d'	Index of sensitivity to stimuli change
β	Index of decision threshold
p	*p* value for statistical significance
F	F value index of statistically significant difference between two means
n	Sample size
R^2	Coefficient of determination measure of how close the data are to the fitted regression line, the highest the better the fit.
X	Multiplicative term in regressions: "by"
M	Mean

LIST OF ABBREVIATIONS

Abbreviation	Meaning
Sample naming	
RD / RDs	Group with dyslexia
nRD/nRDs	Group without dyslexia
Younger	Subjects 7-12 years old
Older	Subjects 13-24 years old
Tasks at study	
VS	Visuospatial (all-encompassing non-language-based skills mainly the 7 VS skills studied presently)
LB	Language-based (all-encompassing language-based skills)
Measures	
ELEQ	Early Life Experience Questionnaire
	Weshler Abbreviated Scale of Intelligence
WASI [FIQ, VIQ, PIQ]	Full Scale Intelligence Quotient Verbal Intelligence Quotient Performance (non-verbal) Intelligence Quotient
WRATspell, WRATread	Wide Range Achievement Test Spelling and Reading tasks
3DIS	Three Dimensional Impossible Tasks
WT	Windows Test
Skills	
SV	Spatial Visualization
SR	Spatial (mental) Rotation
FC	Global Holistic Processing, Speed of Closure, and Flexibility of Closure
DW	Drawing
TR	Target Recognition
PR	Pattern Recognition
N	Navigation
O	Other
Statistics	
ANOVA	Analysis of Variance (statistical test of how much groups differ in their means)
SD	Standard deviation (measure of how much an entity deviates from the mean of all entities considered)
Measures	
Pretest	Tasks scores prior to training
Post-test	Tasks scores after training
Accu	Accuracy (number or mean of correct responses)
RT	Response Time (speed of choice and action to submit a response to stimuli in problem presented on the screen)

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CURRICULUM VITAE

EDUCATION

Ph.D **University of California Merced,** Developmental Psychology
2012-2018

Supervisor Dr. Jeffrey Gilger
Dissertation Topic: Visuospatial Learning in Dyslexics
2nd Year Masters level project: Children's Body Image in Drawing Self
(Supervisor Dr. Tiemensma)
1st Year project: Children Questions and Cognition
(Supervisor Dr. Chouinard)

M.A **La Sierra University,** Teaching Credential (In Progress) 2007-2012
M.A **La Sierra University,** Counseling (+ partial licensing credits) 2007-2012
B.A **Montpellier 3 - Paul Valery University,** (France) Psychology 2005

RESEARCH EXPERIENCE

2012-Present Graduate Student Researcher, University of California Merced, Merced CA

- In charge of undergraduate research assistants, lab organization, research design and implementation, data collection and analysis.

2010-11 Graduate Student Researcher

- *University of California Riverside* | Coding and Data Entry
  Research Supervisor: Dr. Tupett Yates
  Childhood Representation and Regulation Project (CHIIRP)
  Children's representation of themselves and their regulation mechanisms in adversity
- *Loma Linda University* | Experiments & Data Collection
  Research Supervisor: Dr. Haerich,
  Emotion and attention correlations in the absence or abnormality in emotional arousal
- *La Sierra University* | Experiments & Data Collection
  Research Supervisor: Dr. Kim,
  Development of implicit and explicit commonsense physical knowledge in infants

TEACHING EXPERIENCE

Spring 2018 Lecturer at CalState University Stanislaus, Turlock CA

- Taught Development and Ageing, Introduction to Social Psychology, and Cognitive Psychology.

2017-2018 Teaching Fellow, University of California Merced

- Taught diverse classes as assigned by supervising professor
- Organized discussions, created exams and proctored, lead review sessions and group activities,
- Monitored lab work and in class assignments,
- Monitored the online class platform (for students inquiry, discussions, calendars, grading and assignments), graded, and other class duties.

Summer 2017 – Taught Psychology 130 (Upper Div. Developmental Psychology), UC Merced

- Taught child and adolescence development for a 45 students class.
- Taught course, office hours, advising, and assessing learning progress enhanced with Canvas

online class management Platform.

- Used classroom technology such as virtual children to raise, videos, clickers and more to enhance interactivity and learning.

Fall 2014 Adjunct Faculty, Merced College, Merced, CA

- Taught Guidance 30 (Preparation course for college), and followed up with highschool students wanting to apply to college.

2013 - 2017 Art Consultant and Teacher ~ Boys and Girls Club of Merced, Merced CA

- Held classes for 1st to 12th graders. Taught art techniques, and lead annual Art projects.

2012 – 2017 Teaching Assistant, University of California Merced

- Graded, advised students, filtered students emails, managed the teaching interface CANVAS, created exams, quizzes and reviewed sessions, taught classes, lead weekly group discussions, proctored exams, relayed all issues to the Professor of Instruction.

  - **Psychology 001** ***Introduction to Psychology***, for Dr. Altman
  - **Psychology 130** ***Conceptual Development***, for Dr. Chouinard
  - **Psychology 159 -** ***Personality Psychology*****,** for Dr. Yancey
  - Guest lecturer: "Erik Erikson" October 2013
  - **Psychology 123 -** ***Alcohol, Drugs, and Behavior*****,** for Dr. McDiarmid
  - Guest Lecturer: "Schizophrenia & Depressive Illnesses" March 2014
  - **Psychology 150 –** ***Culture and Psychology*****,** for Dr. McDiarmid
  - Guest Lecturer: "Native Indian, African American & Latinos Immigration" March 2014, & "Hispanic, Asians, Arabs and Jews' Cultures" Nov. 2014
  - **Psychology 133 –** ***Neurocognitive Disorders*****,** for Dr. Gilger
  - Guest Lecturer subject: "Autism" April 2015
  - **Psychology 181 –** ***Clinical Neuropsychology*****,** for Dr. McDiarmid
  - Guest Lecturer: "Emotion and the Brain" October 2015
  - **Psychology 183 –** ***Behavioral Genetics*****,** for Dr. Gilger
  - Guest Lecturer: "Genetics and Ethics" October 2016
  - **Psychology 001 –** ***Intro to Psych*****ology,** for Dr. Tiemensma
  - Guest Lecturer: "Perception" February 2017
  - **Psychology 240-03 –** ***Abnormal Psychology*****,** for Dr. J. Emory – Fall 2017
  - **Psychology 015 –** ***Research methods*****,** for Dr. Ross Avilla – Spring 2018

2012-2014 Tutor at Sureprep, Merced California

- Visited low-income families and provied free tutoring for struggling students (Math, English).

2007-2012 Faculty office Assistant, Fayetteville, AK / Riverside, CA

- Editing & proofreading (lectures, recommendations, grants, speeches), events and conference travels organization, supplies order.

2006-2007 Illiterate Adults Instructor, Guadeloupe (French Caribbean)

- NGO PLAC 21 Math and French rehabilitation courses

COUNSELING EXPERIENCE

2011-12 Telecounseling Center Manager, La Sierra University, Riverside CA

- Supervising Multicultural Telecounselors team
- Prospect students academic guidance
- Application and admissions procedures guidance

- Drafting and implementing work policies and office ethics
- Yearly and quarterly projects supervision
- Enrollment statistics reports
- Financial estimates and scholarship planning for students

2009-12 International Relations and Graduate students Assistant Counselor, La Sierra University, Riverside CA.

- Supervised team of Recruiters (worldwide)
- Followed up with prospective and current students
- Located and created contracts with agencies and schools to increase international students attendance
- Hotline support for incoming and current students

2009-10 Group Home Therapist Trainee, Chino, CA.

- Conducting weekly group and individual counseling sessions for residents.

OTHER PROFESSIONAL EXPERIENCE

2015-2017 Program coordinator for Partnerships for Improving Community Health (PICH) Grant provided by the Center for Disease Control (CDC) and the Merced Public Health Department

- Lead a team of college and highschool young activists in education-based actions against youth tobacco consumption and exposure in youth clubs, churches, schools…/…
- Worked with landlords and public housing manager to help set up non-smoking policies
- Worked on participating in public hearings at the city council to encourage the adoption of laws prohibiting the sale and advertisement of tobacco around highschools in Merced, CA
- Anti-smoking educational activities and classes with youth and parents
- Worked with local corner stores and convenient stores to bring affordable fresh fruits and vegetables to underserved communities

PUBLICATIONS

Publications

Crogman, H., & **Trebeau Crogman, M.** (2016). Generated questions learning model (GQLM): Beyond learning styles. *Cogent Education*, *3*(1), 1202460.

Crogman, H., **Trebeau Crogman, M.**, Warner, L., Mustafa, A. and Peters, R. (2015). Developing a New Teaching Paradigm for the 21st Century Learners in the Context of Socratic Methodologies. *British Journal of Education, Society & Behavioural Science, 9*(1).

Trebeau-Crogman, M., Gilger, J., Hoeft F. (2017). *Visuo-Spatial Skills in Atypical Readers: Myths, Research, and Potential (Chapter 14).* In Kaufman, S.B. (2017). *Supporting and Educating Twice-Exceptional Children.* Oxford University Press; 1st Ed (February 1, 2018). **ISBN-10:** 0190645474 **ISBN-13:** 978-0190645472. https://tinyurl.com/y8kup3pw

Publications Under Review

Crogman, H., **Trebeau-Crogman, M.** (2018). The Generated Question Learning Model.

Trebeau-Crogman, M., Eperson, A., Tiemensma, J. (2018). Association of body satisfaction and size with depression in ethnically diverse rural youth.

Manuscripts in Writing

Trebeau-Crogman, M. (2018). Personal 3-Dimensional Location in Reading Disability.
Trebeau-Crogman, M., Gilger, J., Castillo, A. (2018). Visuo-Spatial Skill in Youths with Dyslexia, What We Know and What We Must Find Out.
Castillo, A., Trebeau-Crogman, M., Gilger, J. (2018). Perceptions of Developmental Disabilities in Cultural Contexts.
Trebeau-Crogman, M. (2018). Children's Questions and Curiosity in Learning Life Cycles, How Do Kindergartners Follow Up On Unsatisfied Need For Answers?

Posters

Crogman, M., Castillo, A., & Gilger, J. (2016). Adults beliefs about personal and medical controllability of developmental disorders. Presented at the 2017 UCM 4th Annual Psychology Symposium, Merced, CA.
Castillo, A., **Crogman, M.,** & Gilger, J. (2016). Beliefs among adults about the etiology, timeline, and risk factors of dyslexia. Presented at the 2017 UCM 4th Annual Psychology Symposium, Merced, CA.
Crogman, M., Castillo, A., & Gilger, J. (2016). Adults beliefs about personal and medical controllability of developmental disorders. Presented at the 28th Association for Psychological Science Convention, Chicago, IL.
Castillo, A., **Crogman, M.,** & Gilger, J. (2016). Beliefs among adults about the etiology, timeline, and risk factors of dyslexia. Presented at the 28th Association for Psychological Science Convention, Chicago, IL.
Trebeau-Crogman, M., Eperson, A., Tiemensma, J. (2015, April). *Association of body satisfaction and size with depression in ethnically diverse rural youth.* Poster presented at the Society of Behavioral Medicine, San Antonio, TX.
Poster accepted also at the Association for Psychological Science (APS 2015).
Trebeau-Crogman, M., Eperson, A., Tiemensma, J. (2015). Association of body satisfaction and size with depression in ethnically diverse rural youth [Abstract]. University of California Merced Abstract Art and Appetizers of the Annual UCM Research Week.
Trebeau-Crogman, M. (2015). "Rural Ethnically Diverse Children's and Adolescents' Perception of Self Through Drawings". University of California Merced Health Psychology Colloquium.
Kim, I., Cambara, D., **Trebeau-Crogman, M.,** Kwon, E., Lai, H.S. (2011, November). Effects of Executive Function on Search and Prediction for Mechanical Objects. 52nd Annual Meeting of the Psychonomic Society, Seattle, WA.

Symposium Talks

Trebeau-Crogman, M. (2017). A First Look Into How Dyslexics Learn Spatial Information. Fourth Annual Psychology Symposium, UC Merced, Merced, CA.
Trebeau-Crogman, M. (2011, May). The Secretly Tortured: Post Traumatic Related Defensive Avoidance and Somatization in College Students Victims of Emotional Abuse. First Annual Mental Health Conference, La Sierra University, Riverside, CA.

TRAINING

2012-2013 UC Merced Center of Research on Teaching Excellence (CRTE) ~ Teaching Excellence Certificate (in progress)

GRANTS & AWARDS

2018 Jennifer Mendiola Award
2017 Psychological Science Award
2017 Graduate Student of the Year 2017 Award
Featured in the Graduate Dean Diversity Advisory Committee Newsletter for a campaign on diversity leaders at UC Merced
Featured in the PICH Partners Profile Newsletter for my leadership work with PICH, the Boys and Girls Club and the Merced Public Health Department
2016 William Shadish Award
2016 Graduate Fellowship Incentive Award
2013-2014 UC Merced Center of Research on Teaching Excellence ~ Teaching Excellence Certificate Award
2012-2017 Graduate Summer Fellowship Awards
2012-2017 Graduate Travel and Conference Awards

SERVICE

2017 President of the UC Merced Graduate Student Association
Member of the UC Merced Police Chief Search Committee
Appointed voting member on the UC Merced Transportation and Parking Committee
2014 Present Co-founder and secretary of the Institute for Effective Thinking
2013 Present Volunteer at the Boys and Girls Club of Merced, event organizer, Arts and Literacy teacher
2012 Present UC Merced Research Week Committee
Founder and coordinator for the UCM Annual Psychology Symposium
Campus Research Week poster competition judge
2012 - 2013 UC Merced Developmental Journal Talk Club, Co-Founder & Co-Chair
UC Merced Psi Chi Chapter, Academic Program Committee

TECHNICAL SKILLS

- Microsoft, and Apple office management aps
- Data and online class organization (Banner, CROPS, CANVAS)
- Website editing (WIX, MapQuest)
- Software for learning enhancement (Kurzweil, Natural reader, Livescribe)
- Statistical software (R, SPSS, SAS, MPlus, G*Power)
- Literature library organization (EndNote, Mendeley, Zotero)
- Online meeting and conferencing (TeamViewer)
- eBook building (iBooks, Blurb, BookWright)
- Fine arts (iMovie (Clip and video building), Garageband, Photoshop & GIMP)

PROFESSIONAL MEMBERSHIPS

- Society of Behavioral Medicine (SBM)
- American Psychological Society (APS)
- Psi Chi
- Society for Research in Child Development (SRCD)

LANGUAGES

French (*fluent*), **Creole** (*fluent*), **English** (*fluent*), **Spanish** (*intermediate*)

ABSTRACT

Visuospatial Learning Differences: A Study of Children and Adults With and Without Dyslexia. Maryam Trebeau Crogman, PhD in Developmental Psychology. University of California Merced, 2017. Committee Chair, Dr. W. Jeffrey Gilger.

Despite being studied for an entire century, non-verbal visuospatial skills in Dyslexia have not been comprehensively investigated. Studies have focused mainly on adolescents and adults, on aptitude rather than learning processes, and focused mainly on mental rotation and pattern recognition. In this work we highlight why a better understanding of visuospatial skills is capital to the development and support of young individuals with dyslexia, as a population with a very unique neurocognition. We also piloted an alternative research design to better address the gaps encountered in our review of the existing literature, and model a new approach to studying visuospatial skills in dyslexia. The results of our study indicate a difference in processing and learning between participants with and without dyslexia, as well as an interesting progression of the visuospatial skills tested across age.

CHAPTER I

Introduction

Sitting across the table from me is 15-year-old, TJ[1], soft-spoken and hiding behind his long dark hair. I am in awe as he effortlessly proceeds through a number of visuospatial and language-based problems with agility, computing angles, and patterns and speedily solving hard problems. On one of the tasks, which most adults never finish, TJ finishes with the highest score. Yet, he struggles with the next portions of the session. After being given a written, and spelling task, TJ stalls. He keeps his head down, staring at the list of words. After a few minutes, he slowly raises his head and anxiously says to me, "just so you know, I can't read."

This case illustrates the common reality for children and adults with dyslexia: perfectly able cognitive abilities in oral and non-language-based skills, but difficulty with phonemic awareness (ability to manipulate phonemes in reading, spelling and writing). The issue is not simple. Research on dyslexia reveals consistent genetic, neurological, and behavioral results that set people with reading difficulties apart and as having a unique, characteristic profile (Démonet, Taylor, & Chaix, 2004; Ramus, 2004; Schumacher, Hoffmann, Schmal, Schulte-Korne, & Nothen, 2007; Shaywitz & Shaywitz, 2005; Smith, 2011). Developmental reading disability (RD) is a language processing learning dysfunction, one of the most common learning and reading disabilities in young populations, representing 7 to 10% of the population between primary school and high school grades (Shaywitz & Shaywitz, 2005; Smith, Gilger, & Pennington, 2002).

Historically, medical doctors first observed the symptoms of dyslexia and formulated theories about its origin (Rusiak, Lachmann, Jaskowski, & Van Leeuwen, 2007). There was an inclination to address observable symptoms in a disease-cure fashion. This was necessary, but created a historical dynamic of learning disability perception that still influences researchers, and true to this approach, most of the research since has focused on the dysfunctional aspects of RD and the challenged learning of Language-based information. The important data on the phenotype and linguistic learning profile of people with RD, has initiated the creation of many successful academic training programs (Ehri, Nunes, Willows, Schuster, Yaghoub-Zadeh, & Shanahan, 2001; Melby-Lervåg, Lyster, & Hulme, 2012; Snowling, 2013). Colaterally, while there is research focused on nonlinguistic, physical, and cognitive origins and manifestations of RD (e.g., visual or cerebellar theories of learning in RD individuals; Nicolson, Fawcett, & Dean, 2001; Ramus, Rosen, Dakin, Day, Castellote, White, & Frith, 2003), these theories are not well accepted in current academic circles, and less applied to training programs. That said, no one has yet reconciled the current linguistic deficit understanding of RD with the many reports of RD differences in nonlinguistic neurological and cognitive systems (Gilger, Allen, Castillo, 2016).

While there is a large body of research that shows how and why language-based learning processes are dysfunctional in RD, empirical data are limited regarding the performance (and etiology) of non-language-based visual-spatial processing in RDs. Yet it is clear that visual-spatial cognition is a key piece in brain-based abilities needed for school (and reading) performance. To better address how to support individuals with RD, especially youth who may have unrecognized abilities masked by reading difficulties, training, or compensation, researchers must understand how non-Language-based processes develop as well. This work should focus on visual-spatial (VS)

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[1] Participant TJ is a fictitious construction based on a number of typical cases in this study.

learning issues across development (Gilger, Allen, & Castillo, 2016; Lyytinen et al., 2001). To take advantage of developmental periods and provide strengthening of VS abilities, it important to determine when these skills arise and to what extent they are part of an RD profile. With this in mind, later sections of this dissertation take a careful look at what has been researched in the domain of VS skills in RDs.

I.1. Dyslexia: Definition and Limitations

In the following sections, we briefly address two aspects of the RD profile and learning ability question: Language-based/language-based (LB) and non-language-based/visual-spatial (VS) cognition. These sections provide a theoretical and methodological rationale for our direction of research by elaborating on a definition of LB and VS, a discussion of RD neurology, and a discussion of the importance of considering training to address RD VS learning skills.

Common definitions of RD focus almost exclusively on LB skills. For example:

Dyslexia is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience that can impede the growth of vocabulary and background knowledge. (Lyon et al., 2003)

Dyslexia is a learning difficulty that primarily affects the skills involved in accurate and fluent word reading and spelling. […] characteristic features of dyslexia are difficulties in phonological awareness, verbal memory, and verbal processing speed. […] is best thought of as a continuum, not a distinct category, and there are no clear cut-off points. Co-occurring difficulties may be seen in aspects of language, motor-co-ordination, mental calculation, concentration and personal organization, but these are not by themselves markers of dyslexia. (Rose, 2009)

Both definitions focus on RD as a language-based problem with an additional mention of broader aspects of social and cognitive development. Based on the definition, research has focused on the deficit of Language-based and phonological abilities as a priority in RD. However, this "narrow" definitional focus is limiting, as it does not reference deficits or differences in broader cognitive skills, particularly the non-Language-based and VS aspects of the RD profile. Yet, researchers found that these areas may indeed be part of the RD cognitive profile (Bannatyne, 1976; Buchholz & McKone, 2004; Craggs, Sanchez, Kibby, Gilger, & Hynd, 2006; Fawcett, Nicolson & Dean, 1996; Gilger & Olulade, 2013). Focusing on Language-based difficulties was common for over a century without much consideration for the genesis of other non-Language-based functions that make up the diversity of RD brains (Rusiak et al., 2007). Children with RD often receive educational interventions focusing on reading-related skills and not other skills that may also need remediation or that could be successfully advanced toward helping the RD individual in school and career.

I.2. Neurology of Language-based Processes in RD

Along with the emergence of oral language-based skills, humans developed immensely complex brains and a tendency to neurologically divide labor to perform different types of tasks

(Geary & Gilger, 1989; Gilger et al., 2016; Gilger & Hynd, 2008; Wolf & Stoodley, 2008). Reading is not an ability that arose as a natural artifact of human development. It is a fairly recent cognitive achievement that relies on multiple neural networks primarily set for oral language, in addition to visual-spatial networks (Price, 2010). Given the broad natural human neurodiversity, some researchers proposed viewing brains of people with RD not as abnormal but as belonging to a continuum of brains (Gilger & Kaplan, 2001; Rose, 2009) along with a normal developmental spectrum in the population. Researchers have, in fact, struggled to find consensus on unique RD neurocognitive signatures that could account for the multitude of skills and brain functions differences reported in individuals with RD.

The language-based profile of people with RD is fairly well understood, but researchers have not accounted for high rates of comorbidity (e.g., attention deficit disorder or twice exceptionality) and variance in other cognitive domains. Part of the complexity is due to the complexity of neural pathways that process these skills. Two meta-analyses noted that learning to read, from a cortical perspective, is a function of many brain areas in both hemispheres (Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Richlan, Kronbichler, & Wimmer, 2009, 2011). Structural and/or functional atypicalities appeared in cortical areas that play a role in both LB and VS processing.

Mainly portions of (a) the frontal lobes controlling functions such as speech, planning, and reasoning; (b) sections of the parietal lobes responsible for functions such as sensory perceptions and the linking of spoken and written language and memory with a significant contribution to the attribution of meaning to stimuli;(c) occipital lobes involving visual processing of symbols and text; and (d) temporal lobes involved in language-based functions and memory. Abnormalities also appeared in converging areas or networks such as the parietotemporal and occipitotemporal regions involved in word analysis, letter-sound mapping, fluency and access to words, and naming of objects (Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Richlan, Kronbichler, & Wimmer, 2009, 2011). Thus, Language-based and non-Language-based development is dependent upon complex systems that sometimes function in what may appear to be conflicting domains or, certainly, domains not limited to the processing of text.

Researchers have difficulty detecting early RD in children because the underlying processing difficulties appear gradually as reading demands arise. Yet, the origin of RD neurology begins early in development and exists prior to birth. Post-mortem and in-vivo brain imaging studies found that atypical formations (and concomitant atypical functions) begin by the second trimester in utero (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Hynd, Semrud-Clikeman, Lorys, Novey, & Eliopulos, 1990; Ramus, 2004). This suggests that the behavioral and cognitive process differences in RD originate in gestational environments and must traverse critical phases of pre and postnatal development. Skills undergo many transformations as young RD grow and compensate for early reading difficulties (Eckert, 2004; Galaburda, 1992; Humphreys, Kaufmann, & Galaburda, 1990; Keller & Just, 2009). Using ERP and language perception tasks, Lyytinen et al. (2001) found that the earliest functional/behavioral differences between normal readers, or as we will call them throughout non-reading disabled (nRD) children, and children at risk of dyslexia by 8 weeks of age, while other developmental milestones were not different before age 2. With new technology for brain imaging and genetics/epigenetics, research is progressing and providing earlier diagnostics and predictions for young individuals at risk for developing dyslexia. The brains of people with RD are broadly atypical, and there is a diffuse brain development profile for people with RD with likely non-negligible differences in overall processing (Eckert, 2004; Galaburda, 1992; Humphreys et al., 1990; Keller & Just, 2009; Lyytinen et al., 2001).

Although there is a vast literature confirming the phonological, language-based aspects of the disorder, with support from neurological studies, we (and others; Eckert, 2004; Galaburda, 1992; Humphreys et al., 1990; Keller & Just, 2009; Lyytinen et al., 2001) have suggested that there is much more to the RD phenotype and RD brain. What remains unexplained or inadequately studied are the effects the numerous early developing cortical malformations and structural deviations found outside of the 'reading network' and how these may affect functions outside the reading domain. Indeed, this atypical neurological processing in people with RD is not exclusively in the common left hemispheric Language-based/reading pathways, but in the right hemisphere VS pathways as well (Maisog et al., 2008). Thus, considering the learning disabilities or abilities of people with RD almost exclusively from an LB left hemispheric point of view is problematic in several ways. Moreover, the effects of the RD neurology do not seem to be limited to reading, as there is a high degree of comorbidity associated with the disorder (Pauc, 2005). Similarly, other neurodevelopmental disorders, such as Attention Deficit Hyperactivity Disorder, Autism Spectrum Disorder, and exceptional processing/learning in the gifted range, also show related neurological deviations although they may vary in region, degree or connectivity (cite another ref on the neurology of add, etc.; Treffert, 2009). This raises the question as to how phenotypically distinct disorders can share common neurological underpinnings and why this may be the case.

I.3. Learning and Training

Individuals with RD rely more often on the right hemisphere to read than on the common left hemispheric processing areas (Maisog et al., 2008; Shaywitz & Shaywitz, 2005, 2007; Simos et al., 2002). Reliance on the right hemisphere is part of the normal learning-to-read trajectory; as people age, they shift away from the right to a heavy reliance on the left (Pugh et al., 2000). People with RD, however, maintain this atypical right hemisphere profile. Yet, they can shift or at best come up to par with non-challenged readers' performances with intensive remediation (Breznitz et al., 2013; Keller & Just, 2009). These brain regions that process reading atypically in RD are not specifically pre-wired for that task, as they play a part in the processing of non-Language-based information as well (e.g., for example, the dorsolateral prefrontal cortex, parietotemporal, occipitotemporal, and the anterior cingulate which typically process functions such as stimuli interactions, working memory, motor planning, abstract reasoning, and decision making) (Lurito, Kareken, Lowe, Chen, & Mathews, 2000). It is likely that, while these atypical configurations are part of the RD neurology, they may also influence the course of non-language-based learning. This is particularly true for right hemispheric regions where reliance on these cortical areas might create significant conflicts or overlaps that challenge or enhance non-language-based or VS processing. For example, significant overlaps exist between cognitive structures responsible for learning to read and those devoted to processing and learning spatial information (Horowitz-Kraus & Holland, 2015; Keller & Just, 2009; Kujala et al., 2001; Lorusso, Facoetti, Paganoni, Pezzani, & Molteni, 2006). Cortical modification in some of these areas by practice, training, and learning opportunities changes the domains that pertain to a priori unrelated functions (Gilger, Talavage, & Olulade, 2013).

Current ecological and biological evidence supports that having RD does not simply mean struggling with LB cognitive processes (Brosnan, Demetre, Hamill, Robson, Shepherd, & Cody, 2002; Davis, & Braun, 2010; Eden, Wood, & Stein, 2003; Eide, 2013; Gilger et al., 2016; Gilger et al., 2013; Olulade et al., 2012; Rusiak, et al., 2007; Sigmundsson, 2005; Von Károlyi, Winner, Gray, & Sherman, 2003; West, 1999; Winner, von Karolyi, Malinsky, French, Seliger, Ross, & Weber, 2001). Rather, the challenge of RD is all-encompassing for the brain. For example, McBride-Chang et al. (2011) argued that in young children, better readers are better visuospatial problem solvers.

They posit that these VS abilities were better stimulated in their Chinese subjects as they came to learn an orthographic alphabet in comparison to English readers who rely more on a language based orthography. Accordingly, less skilled readers should also show decreased abilities in VS domains. Thus, researchers may benefit from considering non-LB learning and processing to gain a more balanced approach to addressing dyslexia and RD.

I.4. Non-Language-based Visuospatial Skills in RD

Non-language-based spatial abilities are difficult to define given their range and complexity. Generally, spatial abilities concern the processing of shapes, locations, paths, and relations among non-Language-based entities and relations between entities and frames of reference (Hegarty & Waller, 2005). This information can be "mentally transformed to aid in manipulating, constructing, and navigating the physical world" (Newcombe & Shipley, 2014, p. 180). The term visuospatial skill or ability is "the ability to generate, retain, retrieve, and transform well-structured visual images" (Lohman, 1996, p. 3). The present work specifically focuses on types of VS tasks that require aptitudes in spatial relations (SR), spatial orientation, spatial visualization (SV), closure speed, perceptual speed, visual memory, and kinesthetic left-right orientation. These tasks are inclusive of cognitive strategies (e.g., discriminating pattern frequencies, encoding, remembering, transforming, matching attention, or creativity). This categorization expanded to include VS dynamic versus static visuospatial tasks and navigation in 3D space and virtual environments (Gilger et al., 2016; Newcombe & Shipley, 2014; Uttal et al., 2013).

It is suggested that these many VS skills may have occupied the majority of cognitive processing in human history when reading was not a social mandate and many daily tasks relied on understanding and manipulating spatial information to survive (e.g., aiming at targets, mapping space, building tools and buildings, handy work). Therefore, there is great population variation in VS skills, a domain developed and maintained through changing environmental demands across eras.

We argue that based on this variability and evidence of RD atypical cognitive experience, appropriate education for RDs cannot be complete without a comprehensive map of an RD cognitive/learning profile that includes both LB and non-language-based abilities and challenges. More so, children with RD should be a population of interest in empirical settings because of their cognitive plasticity and the possibility to observe how they develop VS and LB functions together.

What can researchers learn about VS learning abilities to support children's development in educational, professional, and social realms? Some educators, parent advocates, and researchers pushed back against labeling dyslexia as a disability and highlighted that such individuals show certain behavioral patterns, giftedness, or superior abilities in VS skills. They contend that people with RD are actually commonly gifted (Davis, & Braun, 2010; Eide, 2013; von Károlyi, Winner, Gray, & Sherman, 2003; West, 1999), and inherently talented in non-Language-based areas. Accordingly, this could explain why people with RD may adopt and excel in VS-oriented professions involving mathematical and artistic skills or in people-oriented positions (Cowen, 2014; Eide & Eide, 2011; Logan & Martin, 2012; Taylor & Walter, 2003; West, 2009; Wolff & Lundberg, 2002). Additionally, an elevated number of individuals with RD have been observed to choose or pursue non-Language-based careers (e.g., fine arts, astronomy) or people-oriented careers (e.g., nursing, business), perhaps related to these special aptitudes (West, 1997; Winner, Casey, DaSilva, & Hayes, 1995). However, these findings are largely drawn from non-empirical work, anecdotal accounts, or self-report surveys. The etiology of this trend could be something other than biologically-based and non-language-based superior abilities, such as limited options in advanced schooling (real or perceived).

Marazzi (2011) contends that people with dyslexia contribute uniquely to the economy and their special non-language-based abilities are an asset. However, there is a clear lack of empirical information on, and support for, the VS-gifted dyslexic hypothesis. As the reader will see below, the literature review conducted for this dissertation shows actually the opposite, at least for the classic VS-based skill domains. However, the lack of research on other VS skills makes the picture incomplete and makes it difficult to draw any definite conclusion.

In summary, there is a paucity of experimental research studies in RD VS skills and career. This lack of information and data causes a lack of consensus about how to treat RD individuals beyond their reading problem, and the field may miss important supporting structures that could improve the lives of people with RD by more fully developing their cognitive potential to contribute to society.

I.5. Neurology of Visuospatial Processes in RD

According to early studies, certain neurodevelopmental structural patterns result in RD and may yield better than average nonlinguistic skills (Geschwind & Behani, 1982; Geschwind & Galaburda, 1987; Galaburda, 1992). Geschwind and others hypothesized that there may be an etiological link between Language-based deficits and spatial skills in the non-language-based domain (Geschwind & Behani, 1982; Geschwind & Galaburda, 1987; Galaburda, 1992). These theories stemmed from observing cortical hemispheric differences in gender groups and associating them with gender-specific cognitive abilities. At that time, it was believed that developmental hemispheric differences were prominent in people with RD, especially in males who had a higher prevalence of RD in the population. This finding was then linked to the higher mean VS performance in males and was proposed to account for both reading disability and VS giftedness (Geschwind & Galaburda, 1985). According to these authors, pathological or atypical development of the left hemisphere, and secondarily the right hemisphere, along with neurological compensation, could lead to language-related weaknesses and non-Language-based strengths.

Individuals with RD also show nonlinguistic behavioral deficits and concomitant differences in structural neurology (in and outside the left hemisphere reading pathway) that may contribute to reading difficulties. These areas are related to visual-orthographic processing, cognitive-temporal sequencing, and anatomical variations of the parvo-magnocellular system (Fawcett & Nicolson, 1994; Howard, Howard, Japikse, & Eden, 2006; Schneps, Brockmole, Sonnert, & Pomplun, 2012; Skottun, 2005; Stein, 2001;). While there is a basic understanding of how neurological differences manifest in the functional aspects of reading (Démonet et al., 2004; Shaywitz & Shaywitz., 2005; Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006), how these structural and functional deviations may relate to other behaviors or cognitive capacities is unknown.

Furthermore, even if RD and nRD individuals perform similarly on VS tasks, their functional neurology while solving such problems can be quite different (Diehl et al., 2014; Gilger et al., 2013; Olulade, Gilger, Talavage, Hynd, & McAteer, 2012). Just as RDs have signature functional neurology for the left hemisphere reading pathway, they also exhibit unique neurological profiles in their processing of VS stimuli. For instance, Olulade et al. (2012) and Gilger et al. (2013) reported reduced activation in bilateral parietal regions (i.e., areas involved in complex dynamic VS processing) of RDs relative to controls. Diehl et al. (2014) used the same and different VS tasks to show RD-nRD neurological differences and found similar RD-nRD differences.

Gilger and Hynd (2008) and Gilger et al. (2013) proposed that the neurological signature in Older RDs for VS skills could be the residual of the developmental neurology that leads to dyslexia, but proposed that it changed with age, experience, and compensation for reading weaknesses. If there is an RD neurology that makes people deal with spatial information differently (as it does for dealing with reading, writing, and spelling), then it is important to ascertain if RDs learn how to process VS information differently like they do with text (Schneps et al., 2011). Additional research regarding how VS neurology of RD individuals change with practice or training, and how this may differ from that of nRDs, is necessary, especially for early age groups (Olulade et al., 2012; Gilger et al., 2013), yet our literature review has shown a lack of research on young children in the VS domain.

Literature Review

II.1. Literature Review

To begin to understand the gaps in the current literature on RD learning abilities in the non-Language-based VS domain, this section details a comprehensive literature review evaluating and qualifying existing empirical data on VS skills in people with RD compared to controls (nRD). This work was aimed at highlighting potential gaps in what has been done before, such as the types of tasks used in prior research (paper-pencil /technology), limited age groups of focus (developmental trends), types of skills assessed (dynamic/complex vs. static and simple), and limitations to crystalized or more fluid cognitive processes (learning/performance).

Further details are provided below, but we can summarize our conclusions as follows: 1. There is a focus in the literature on classic paper-and-pencil tasks even though more diverse VS skills could be tested; 2. Studies investigating age trends in the development and learning of VS skills are essentially absent; and, 3. Nearly all studies involve single or one-time measures of aptitude, and do not track the effects of practice or extended performance. The issues discovered prompted the creation of a longitudinal study to evaluate VS learning outcomes in children and adults with RD, and promote discussions and for a better understanding of these processes via more investigation of learning processes in people with RD. This study was carefully designed to address the three issues mentioned above by using both static and dynamic tasks, across a wide range of age, and looking at both single time performances and learning trends at the same time.

This literature search investigated VS skills in people with RD spanning over 40 years (1975 to 2016). Databases for this search included EBSCO, PsychInfo, PsychArticles, and Google Scholar. The bibliographies of identified articles were crosschecked with database results to help ensure that no significant articles were missed. Key words included: dyslexia, twice-exceptionality, giftedness, reading disorder, reading disability, spatial, spatial ability, spatial aptitude, visual-spatial talent, non-Language-based skills, ability, aptitude, VS learning, VS training, VS tasks, spatial, performance, rotation, visualization, VS skills, intervention, and training. Like Gilger et al. (2016), we accepted and reviewed only those studies that included a control/nRD comparison group. Excluded from this review were any other publications that did not allow for that distinction or were not peer reviewed empirical work. Excluded from this review are books, chapters, conference presentations, single subject case studies and anecdotal reports (except where specifically identified otherwise in this article), and publications with a primary focus on motion perception, visual memory/attention, peripheral abilities, perception of spatial frequencies, and function of the parvo-magnocellular systems as these do not fit our definitional criteria for dynamic and complex spatial reasoning. Publications may have been missed that included a means to assess spatial skills in subjects with RD if they did not match-up to our key words. A likely candidate in this category would be studies that included measures of non-Language-based IQ that were not a focus but were part of the context of a larger study looking at other qualities in RD samples.

The search yielded 204 articles, books, reports, abstracts, and other works. A total of 48 articles met the selection criteria, with 204 RD/NRD task performance comparisons[2]. Participants tested in these studies ranged from 4 years old to adulthood and accounted for a range of populations, genders, and participant backgrounds.

II.2. Tables and Summary of Findings

Table 3 data is derived from prior factor analytic work (Lohman, 1996). It illustrates seven main categories of VS skills and a synthesis of tests that correlate with the same underlying set of processes. Each category has an acronym to simplify Tables 1, thru 4: spatial visualization (SV), spatial relations/rotations (SR), global holistic speed/flexibility of closure (FC), drawing (DW), pattern recognition (PR)/target recognition (TR), virtual/3D navigation (N), other (O). Table 4 shows a detailed summary of each of the 48 articles in the literature review by authors, the age range of participants, the tools, and study findings regarding RD groups. Table 5 summarizes the findings from Table 4 in numeric form and provides a summary of the overall average performance of individuals with RD compared to nRD controls on the 187 VS task comparisons in the review.

Of 187 VS tasks across the 48 studies, individuals with RD demonstrated superior performance over controls on 35 comparisons (18.7%), lower performance on 81 (43.3%), and equal performance on 71 (38%). People with RD, when tested on VS performance against controls, do not typically outperform nRDs. In fact, individuals with RD perform equal to or worse than nRDs more than 81% of the time. When RDs performed better, it was on tests of global/holistic processing (rapid identification of spatial distortions) and pattern recognition (perceptual organization) over 63% of the time better than nRDs (see also Gilger et al., 2016). Notable also were the findings concerning Response Time (RT) and Accuracy. A total of 11 studies particularly focused on reporting these two indices of performance. Here again, RDs had better RT only in four studies, they had worse RT in 7 studies and worse accuracy rates in 6 studies; finally, RDs performed equally in 3 reports of RT and 7 reports of accuracy across all tasks comparisons.

The literature search resulted in finding studies that only tested RD and nRD groups on their performances/aptitude at single time points. Researchers focused on aptitudes, neglecting for the most part learning abilities by following how RDs could assimilate VS information and strategies, and integrate them to solve new problems. If there was superior VS ability in RDs it is in this type of context that their unique VS cognitive processes could be observed.

A few studies tested RD and nRDs over several sessions but focused mostly on non-dynamic or non-complex 2-dimensional VS tasks, such as pattern or target recognition, and did not look at the strategies that RDs learned or improved through training to determine if their outcome were specific to an RD profile or even had transferred to other skills domains (e.g., Language-based domains, which is a topic of interest for the present investigation). For example Howard and

[2] Some papers included more than one VS test to compare RD to nRD on VS tasks. There were 187 useable statistical comparisons for VS skills across 48 articles selected.

colleagues (2006), tested participants over one day with multiple practice trials on sequence learning tasks. They emphasized that learning happened for both RDs and nRDs, but that RDs learned less (or seemingly made less use of the problem-solving strategies they acquired), and at a markedly slower pace. This was specifically visible in both their accuracy and response time rates, which are known markers of RD abilities to solve problems. This suggests that RD had a unique response to VS practice, however, these results were still confined to non-dynamic VS materials which does not allow to generalize the result to other VS skills in RD such as in spatial dynamic contexts. Consequently, information is still missing even after these researchers endeavored to study VS learning abilities in RDs.

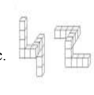
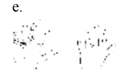
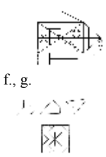
Nicolson and Fawcett (2000) also attempted to look at learning abilities. They investigated RD VS performance with tasks designed to test cerebellar functions. They too used a 2-dimensional practice task. Practice did not include feedback to participants, but training was a year long, with 3 phases of data collection. They concluded that RDs' speed and accuracy were still lower after RDs normalized to the automatization level of nRDs after training.

Franceschini et al. (2013) created a pre-post design geared to improve attention (not VS skills), looking at learning progress using a Wii video game practice. They found that reading skills improved in RDs as a result of strengthening attentional skills. This time the design was more dynamic in its form, which is innovative and should be explored further, however again, no feedback was offered to observe RD/nRD progress over time. Additionally, despite the focus on attentional skills, the interesting idea here is that practicing in a VS domain has had an effect on the LB domain. This is promising and gets back to our idea that the focus should not remain on language-based skills, but that evidence of overlap between LB and VS regions should push researchers to become holistic in their research designs on this question.

Our argumentation so far is that some studies have come close to help mapping RD VS abilities in their various approaches to the question, but too often fell short of addressing all the issues highlighted in our review.

Uncovering the lack of information on RDs' spatial VS thinking skills prompted the creation of the following study to stimulate the field into exploring longitudinal dynamic training research in RDs' VS abilities.

Table 1. Visuo-spatial skills & constructs (a)

Skill	Description	Type	Example Tasks	Studies
Spatial Visualization (SV)	Complex, multistep manipulations of spatially presented information, may involve rotations, dynamic movement, part-to-whole analysis	Paper From Board, Block Design, paper folding	b. 	Thomson (1982); Kamhi, Catts, & al. (1988); Siegel, & Ryan (1989); Everatt (1997); Winner, von Karolyi, Malinsky, et al. (2001); Brosnan, Demetre, et al. (2002); Helland & Asbjørnsen (2003); Duranovic, Dedeic & Gavrić (2014); Lockiewicz, Bogdanowicz, & Bogdanowicz (2014).
Spatial Relations or Rotations (SR)	Perceive an object from different positions, mentally rotate one stimulus to align it with a comparison stimulus, involves rotations and/or reflections	Shephard Metzler Cubes	c. 	Stanley, Gordon et al. (1975); Pontius (1981); Thomson (1982); Corballis, Macadie, & Beale (1985); Eden, Stein & Wood (1993); Singh (1993); Karádi, Kovács, et al, (2001); Winner, et al. (2001); Rüsseler, Scholz, Jordan, & Quaiser-Pohl (2005); von Károlyi & Winner (2005); Rusiak, et al. (2007); Attree, Turner & Cowell (2009); Wang, & Yang, (2011); Olulade, Gilger, et al. (2012); Diehl, Frost, Sherman et al. (2014); Lockiewicz, Bogdanowicz, & Bogdanowicz (2014).
Global-Holistic Processing, Closure Speed, Flexibility of Closure (FC)	Rapid identification of incomplete or distorted pictures & figures impossible in normal 3D environments	Impossible Figures (called in this paper '3DIS'), Gestalt Completion	d. 	von Karolyi (2001); Winner, et al. (2001); Brosnan, et al. (2002); von Károlyi, et al. (2003); Bucholz & McKone (2004); von Károlyi & Winner (2005); Brunswick, et al. (2010); Diehl, Frost, Sherman et al. (2014).
Drawing (DW)	2D drawing or reproduction of shapes or patterns	Draw a man, Free drawing, pattern reproduction	e. 	Pontius (1981); Everatt (1997); Winner, et al. (2001); Eden, Wood & Stein, (2003); von Karolyi et al. (2005); Alves, & Nakano (2014); Duranovic, et al., (2014).
(PR) Pattern Recognition/Recall / (TR) Target Recognition/Recall	Perceptual organization	Matrices, Rey-Osterrieth Complex Figure Task, Hidden Figures, Block design	f., g. 	Rudel, & Denckla (1976); Siegel, & Ryan (1989); Koenig, Kosslyn, & Wolff (1991); Eden, Stein, & Wood, (1993); Everatt (1997); Facoetti, Paganoni, Turatto, Marzola & Mascetti (2000); Fischer, & Hartnegg (2000); Nicolson, & Fawcett (2000); von Karolyi (2001); Winner, et al. (2001); Brosnan, Demetre, et al. (2002); Helland & Asbjørnsen (2003); Bucholz & McKone (2004); Howard, Howard, Japikse & Eden (2006); von Karolyi et al. (2005); Attree, et al. (2009); Brunswick, et al. (2010); Collis, Kohnen & Kinoshita (2012); Olulade, Gilger, et al. (2012); Schneps, Brockmole, Sonnert & Pomplun (2012); Alves, & Nakano (2014); Ruffino, Gori, Boccardi, Molteni & Facoetti (2014); Martinelli & Schembri (2015); Wang, Schneps, Antonenko, Chen, & Pomplun (2016).
Virtual World Navigation/ 3D Navigation / Speed of Recognition (N)	Navigating 2D-3D space	Maze, Navigating virtual environments,	h. 	Siegel, & Ryan (1989); Nicolson, & Fawcett (2000); Sigmundsson (2005); von Karolyi et al. (2005); Attree, et al. (2009); Mammarella, Meneghetti, et al. (2009); Brunswick, et al. (2010); Wang, & Yang, (2011).
Other (O)	Right-left orientation, visuo-motor and visuo-constructive performance, perceptual organization	Finger recognition, Queen's head direction	i. 	Benton (1984); Winner, et al. (2001); Brunswick, et al. (2010); Duranovic, et al., (2014).

Note: some studies appear several times as they tested diverse types of skills. a. Constructs and table format exapnded from Gilger, Allen, & Castillo (2016); b. Modified example from the Minnesota Paper From Board Test (Likert & Quasha, 1941); c. Example from Vandenberg and Kuse (1978); d. Example from Schacter, Cooper, & Delaney (1990); e. Example from Winner et al. (2001); f. Test stimulus from Osterrieth (1944) and Rey (1941); g. Example from Winner et al. (2001); h. Example from Brunswick, et al. (2010); i. Illustration for one of the tasks in Brunswick, et al. (2010).

Table 2. Studies featuring RD performances compared to controls, detailed by Authors, year, Age range, tasks used, and level of performance by type of VS skill tested.

Authors	Sample and Age Group	Tools & Tasks	Higher Performance	Lower Performance	Equal Performance
van Bergen, de Jong, et al. (2014)	212: 100 at risk w/o RD. 44 RDs, 68 controls (Age 4 and 4 years later)	Block Design, Patterns (copying patterns), Object Assembly (jigsaw puzzle), Picture Completion (adding missing parts), Analogies (assembling pieces in small trays by shape, color, size)		PR (Block Design), PR (Patterns), PR (Analogies), SV (Object Assembly) , SV (Picture Completion)	
Kamhi, Catts, & al. (1988)	30, 10 RDs. (6-8)	Minnesota Paper Form Board, paper folding		SV (Minnesota paper), SV (paper folding)	
Siegel, & Ryan (1989)	641, 200 RDs (6-14), Grouped as 6-8, 9-14: Phonics Deficit group (PDG), Comprehension (CDG), Rate DG (RDG)	Block Design, Object assembly, Picture Completion, Picture Arrangement, Mazes, Performance IQ (PIQ)		**PDG:** SV (Block design in PIQ) 6-8, PR (object assembly) 6-8, PR (picture completion) 6-8; **CDG:** SV (Block design in PIQ) 6-8/9-14, PR (object assembly) 6-8, PR (picture completion) 6-8, PR (picture arrangement 6-8); **RDG:** SV (Block designin PIQ) 6-8/9-14, PR (object assembly) 9-14, PR (picture arrangement) 6-8, N (mazes) 9-14	**PDG:** SV (Block design in PIQ) 9-14, PR (object assembly) 9-14, PR (picture completion) 9-14, PR (picture arrangement) 9-14, N (mazes) 6-8/9-14; **CDG:** PR (object assembly) 9-14, PR (picture completion) 9-14, PR (picture arrangement) 9-14, N (mazes) 6-8/9-14; **RDG:** PR (object assembly) 6-8, PR (picture completion) 6-8, PR (picture arrangement) 9-14, N (mazes) 6-8
Rudel & Denckla (1976)	51 nRD, 23 RDs (7-12)	Spatial & Temporal Matching	Spatial-Spatial Matching (PR)	PR (Spatial-Temporal Mtchg), PR (Temporal-Spatial Mtchg), PR (Temporal-Temporal Mtchg)	
Ruffino, Gori, et al., (2014)	75, 32 RDs. (7-14)	Target detection and identification of masked objects		TR (Spatial and temporal attention)	
Tobia, Marzocchi (2014)	160, 32 RDs (7-10)	Visual search: cancel a stimulus in an array. Visuospatial attention (click a button when detecting a dot on screen)		PR (cancel picture in array, RT) TR (spot dot, RT)	Both eccentricity & visual field PR (cancel picture in array), TR (spot dot)
Rüsseler, Scholz, Jordan, & Quaiser-Pohl (2005)	70, 34 RDs (7-9)	FRT 3D figures, symbols, and pictures mental rotation tasks, EFT Embedded figure test		SR (in all 3 mental rotation tasks, & EFT)	
Stanley, Gordon et al. (1975)	66, 33 RDs (8-12)	Visual matching spatial transformation, identify similarities of 3D objects.			SR (Visual matching spatial transformation)
Pontius (1981)	356 children - 104 RDs (8-15)	Bender Gestalt Rotation task, drawing		SR (mental rotation), DW (drawing a person)	SR (mental rotation)
Thomson (1982)	83 RDs (8-16)	British Ability Scales (BAS): Letterlike form rotation, Visualization of Cubes, Block Design (Level), Block Design (Power), Recall of Design.			SR (letter rotation), SV (blocks level), SV (blocks power), SV (cubes)
Benton (1984)	Mulitple studies with children & adults	Show right left limbs, finger recognition		O (right left orientation), O (finger recognition)	
Singh (1993)	40, 20 RDs (8-11)	Mental Rotation		SR (mental rotation)	
Fischer, & Hartnegg (2000)	85 RDs (8-15)	Practice on pattern orientation to detect targets in visual field			PR (Pattern detection after training)

Table 2. Continued

Authors	Sample and Age Group	Tools & Tasks	Advantage	Disadvantage	Equal Performance
Karádi, Kovács, et al, (2001)	55, 27 RDs (8-9)	Angled drawing recognition		SR (mental rotation)	
Duranovic, Dedeic & Gavrić (2014)	80, 40 RDs (9-11)	Mental Rotation, Paper Folding, Rey O. Complex Figures, Electric Grid Task, Drawing memory	SV (Paper folding)	DW (Drawing memory long term but results non-significant)	SR (Mental rotation), PR (Rey O. coplex figure copy), PR (Electric grid), DW (Drawing memory short term)
Mammarella, Meneghetti, et al. (2009)	39, 22 RDs. (9-12)	Outdoor spatial description surveys and route description		N (Outdoor spatial description surveys and route description)	
Alves, & Nakano (2014)	26, 13 RDs (9-11)	Raven Matrices, Figural Creativity			DW (creative drawing), PR (Raven matrices)
Eden, Stein & Wood (1993) – *Book chapter*	17 (10-13)	Complex Figures, Judgment of Lines		SR (judgment of lines)	PR (complex figures)
Eden, Wood & Stein, (2003)	93, 26 poor readers (10-12)	Clock drawing, handedness (Edinburg test), Visuospatial skills (WISC Block design test)		DW (Clock drawing)	DW (Clock drawing)
Wang, & Yang (2011) *3D Study*	120, 60 RDs (10-12)	Columns (cover) a ball (target), must rotate 3D figures to find a ball.	SR, N (rotation response time)		SR, N (rotation accuracy)
Corballis, Macadie, & Beale (1985)	20, 10 RDs (11-13)	Rotation of letters, discriminating Bs from Ds	SR (left hemisphere advantage for un-rotated letter recognition in space)		SR (accuracy)
Corballis, Macadie, Crotty, & Beale (1985)	20, 10 RDs (11-13)	Recognizing rotated F, G, R		SR (1/accuracy letter recognition, more errors with G; results non-significant), (2/speed of recognition (rotated & unrotated) but results non-significant)	SR (letter recognition accuracy & speed of F&R)
Vakil, Lowe, Goldfus (2015) – *Practice study*	53, 23RDs (11-13)	ToH (Tower of Hanoi) puzzle (SV), Pattern skill learning task (PR)	PR (Pattern skill learning task, RT after practice), SV (time by first move aft. pct)	SV (time for moves)	PR (Pattern skill learning task, learning, SV (number of moves to find solution, RT)
Helland & Asbjørnsen (2003)	39 RDs (12-13)	Aston Index (Visual-sequential memory tasks pictures & symbols), WISC (block design, Object assembly)	PR (Visual-sequential tasks for the subgroups with math skills	PR (Visual-sequential tasks) for the mathematics-impaired subgroup, PR (block design), SV (Object assembly)	PR (Visual-sequential tasks for RD subgroup with language & math impairments)

Table 2. Continued

Authors	Sample and Age Group	Tools & Tasks	Advantage	Disadvantage	Equal Performance
Attree, Turner & Cowell (2009) *3D Study*	42, 21 RDs (12-14)	British Ability Scales Pattern Construction & Design Recall tasks (BAS), Virtuality "pseudo-real life test"	PR (spatial recognition memory); N (real world, target recognition)	PR (BAS but results non-significant	SR (Global rotation)
Martinelli & Schembri (2015)	36, 16 RDs (12-13)	Hidden Shapes, Sections, Jigsaws, Wallpaper and Right Angles (Smith & Lord, 2002).	PR (Raven matrices-progressive), PR (Jigsaw), PR (wallpaper, but results non-significant), PR (right angles)	PR (Hidden figures, Sections)	
von Károlyi, Winner, Gray & Sherman (2003)	64, 29 RDs (13-18)	S1 & S2: Impossible Figures Test	S1 & S2: FC (impossible figures, in response time (RT))	S1 & S2: FC (Impossible Figures in accuracy, but results non-significant)	
Nicolson, & Fawcett (2000)	S1: 21, 13 RDs, (13-15). S2: 22, 11 RDs, (15-16).	PacMan maze practice		S1 & S2: PR (Automatization "Strength" after training)	
Diehl, Frost, Sherman et al. (2014)	53 RDs from that 27 did the fMRI (13-22)	fMRI, Mental Rotation (Accuracy & response time), Impossible Figures (Accuracy, response time), Navon Task (Accuracy, response time).	FC (Impossible figures response time out of scanner)	SR (mental rotation accuracy), FC (Navon response time), FC (impossible figures response time & accuracy in scanner)	FC (Impossible figures accuracy), FC (Navon accuracy), SR (mental rotation response time)
von Karolyi (2001)	40 RDs (15-18)	Computerized gloval task (Impossible figures), feature oriented task (Celtic Matching Task	FC (Impossible figures for response time not at expense of accuracy)	PR (Celtic Matching Task but results non-significant)	FC (Impossible Figures for accuracy)
Winner, von Karolyi, Malinsky, et al. (2001)	S1: 60, 21 RDs (15-24). S2: 37, 15 RDs (grades 9-12). S3: 63, 40 RDs	S1: Vandenberg Test of Mental Rotation, Rey–Osterrieth Figure, Hidden Figures. S2: all above + Archimedes' screw, pyramid puzzle, drawing, K-Bit matrices. S3: Gestalt Completion Test, spatial orientation, card orientation, boat test, form board test, figural flexibility (storage task), closure speed, reference memory (maze test)		SR (mental rotation, card rotation (in S3)) SV (Archimedes screw), SV (Form board in S3 if untimed), PR (Rey complex figure in S2 but results non-significant), PR (K-bit matrices in S2), O (storage test), N (Spatial reference memory in maze test)	PR (Rey complex figure), PR (Hidden figure), SV (Archimedes screw) SV (Form board), SR (mental rotation), O (storage test), FC (gestalt completion)DW (drawing hands)
Koenig, Kossly, & Wolff (1991)	12 RDs males (16-18)	Memorizing shape or letters patterns in a grid		PR (letter patterns)	PR (shapes pattern)
Everatt (1997)	36 (18-55)	Spatial Reasoning, Ravens Matrices, drawing	DW (creative drawing)	SV (spatial reasoning), PR (matrices, but results non-significant)	
Sigmundsson (2005) - *3D Study*	23, 10 RDs (18-23)	Simulator car driving while pushing buttons (condition 1) or a voice-activated microphone (condition 2) immediately when a road sign appears		N (response time)	
Brosnan, Demetre, Hamill, Robson, Shepherd & Cody (2002)	S1: 18, 9 RDs. (Mean age 34); S2: 60, 30 (14) RDs. S3: 30, 15 RDs (18-29)	**S1:** Group Embedded figure test GEFT (for inhibition), ToH task (planning); **S2:** Group Embedded figure test GEFT (for inhibition); **S3:** spatial span, spatial recognition, matching complex figures, pattern recognition		S1&2: FC (Group Embedded figure test)	S1: SV (ToH ball task), S3: PR (spatial span), PR (spatial recognition), PR (matching complex figures), PR (pattern recognition)
Facoetti, Paganoni, Turatto, Marzola & Mascetti (2000)	10 adults (mean age 20), 20 children (mean age 10) 10 were RD	Attention on cue changing task		S1 & S2: TR (Longer in RT)	

Table 2. Continued

Authors	Sample and Age Group	Tools & Tasks	Advantage	Disadvantage	Equal Performance
von Károlyi & Winner (2005) - *Book*	S1: 60, 21 RDs (young adults). S2: 37, 15 RDs (college). S3: 63, 40 RDs. (high school); S4 & 5: 64, 29 RDs (Middle and High school)	S1: Vandenberg mental rotation test, Rey Osterrieth & Hidden figures. S2: S1 + Kaufman Brief Intelligence Test matrices (K-Bit), drawing task, 3D puzzle, Archimedes' screw; S3: spatial orientation (Card Rotation, Vandenberg TMR, Boat test), mental visualization (Form Board Task), Figural flexibility (Storage Task), Closure speed (Gestalt completion test), spatial memory (Morris maze); S4 & 5: Impossible figures task.	S4 & 5: FC: Impossible Figures	SR: (Vandenberg test of mental rotation (RD females)), PR (K-Bit matrices), S3: SR (card rotation), SR (boat test when timed), FC (storage test when timed), N (Morris maze)	PR (Rey Osterrieth complex figure); PR (hidden figures); SV (Archimedes' screw); DW (drawing ability); S3: SR (boat test when untimed); FC (storage test when untimed); FC (Gestalt completion)
Howard, Howard, Japikse & Eden (2006)	23, 11 RDs (20)	Alternating serial response time & spatial context learning, computer screens letters and shapes series	PR (pattern recognition in spatial context learning)	PR (pattern recognition in sequence learning)	
Barnes, Hinkley, Masters (2007)	60, 30 RDs (20-30)	Detecting motion in rotated or linear static images on screen, identifying if image presented corresponds to the previous screen picture		SV (perception of static spatial movement organization)	
Rusiak, Lachman et al. (2007)	28, 16 RDs (19, 20)	S1 & 2: Letters oriented differently, press key when stimuli appears		S1 & 2: SR (Letters mental rotation RT)	S2: SR (Mental rotation of shapes)
Buchloz & McKone (2004)	10 RDs, 10 NRDs (College students)	Frequency Doubling Grating; Conjunction Visual Search; Landolt Ring-Gap Detection	Ring-gap detection (FC)	PR (Frequency Doubling), TR (Conjunction Visual Search)	
Brunswick, Martin & Marzano (2010) - *3D Study*	41, 20 RDs (College students)	WAIS PIQ (picture completion, block design, object assembly), Rey Osterrieth Complex figure, ambiguous figure test, Visuospatial knowledge: Queen's head direction, Herman Virtuality environment, Gollin incomplete figure test	PR (PIQ picture completion), PR (Object assembly), FC (ambiguous figure) for RDs men, PR (Rey complex figures), PR (pattern reproduction), O (recallingimage direction) N (navigating), N (recreating virtual environment)	PR (PIQ Block design)	
Stothers & Klein (2010)	49 RDs (college & adults)	Gestalt Closure, Block Design			FC (Gestalt Closure), PR (Block Design)
Schneps, Brockmole, Sonnert & pomplun (2011)	29, 10 RDs (college)	S1: object search in sets, S2: finding objects in real world scenes, S3: finding objects in low-pass filtered scenes	S3: TR (object search in low-pass filtered scene)		S1: TR (object search in set), S2: TR (object search in real world scene)
Collis, Kohnen & Kinoshita (2012)	46, 19 RD, 27 nRD (College)	Partial Report Task	TR (Symbol)	TR (Letter)	
Olulade, Gilger, et al. (2012)	21, 9 RDs (18-25)	fMRI 3D rotation task	PR (WASI PIQ) SR (MRI rotate RT, result was non-significant)	SR (MRI Rotate % accuracy, results non-significant). SR (MRI non-rotate % accuracy and response time, results non-significant)	
Lockiewicz, Bodganowicz (2014)	180 High school upto 30, 93 RDs	The APIS-Z Battery visuo-spatial subtests (2,7), Urban-Jellen Test for Creative Thinking-Drawing Production (TCT-DP)-Polish adaptation.			SV (Test2 square), SR (test7 cube),
Wang, Schneps, Antonenko, Chen, & Pomplun (2016).	36 Undergrads 18 RDs (18-60)	Comparative Visual Search			PR (Comparative visual search both RT and accuracy)

Table 3. Summary of empirical research reports of raw scores or accuracy, and response time results of RD vs. controls performances on VS tasks over 40 years of research. The table classifies by performance levels and types of VS skill.

	RD Superior Performance	RD Lower Performance	RD Equal Performance	TOTAL Tasks Occurrences Per Skill
SV Spatial Visualization	2(8.0)	13(52.0)	10(40.0)	**25**
SR Spatial Relations or Rotations	3(9.0)	15(45.5)	15(45.5)	**33**
FC Global-Holistic Processing, Closure Speed, Flexibility of Closure	8(36.4)	7(31.8)	7(31.8)	**22**
DW Drawing	1(11.1)	3(33.3)	5(55.5)	**9**
PR Pattern Recognition/Recall	14(20.3)	29(42.0)	26(37.7)	**69**
TR Target Recognition/Recall	2(18.2)	6(54.5)	3(27.3)	**11**
N Virtual World Navigation/ 3D Navigation	4(30.8)	5(38.5)	4(30.8)	**13**
O Other	1(20.0)	3(60)	1(20.0)	**5**
TOTAL Tasks Per Performance Level	**35(18.7)**	**81(43.3)**	**71(38.0)**	**187(100)**

Note. x(z): ***x*** represents the number of tasks among the 187 occurrences in the reviewed literature & ***z*** is representative of the percentage over all skills in parentheses. Only 11 studies specifically separated RT and accuracy (details in Table 2). In general researchers reported mostly simple raw scores.

II.3. Summary

The present study extended the work of Gilger et al. (2016) by completing the evaluation of the state of scientific knowledge over the past 40 years of research on RD VS skills. Several clear conclusions emerged. Researchers are encouraged to develop new research directions along those lines in the field of RD to contribute to a more comprehensive picture of RDs' VS abilities.

3.1. Modalities

In over 40 years of RD VS literature, a central issue is the type of skill investigated so far in the form of dynamic/complex vs. static/simple tasks. Researchers tested both types of skills in different capacities in very unequal proportions. There was very little innovation in areas such as virtual/3D RD skills, spatial navigation, and art skills. Whether testing dynamic or static skills, most researchers used paper-pencil testing methods. Other modalities can test these skills in more ecological settings by using more updated available technology. In fact, one study suggests that RDs may excel on tasks with a 3D/interactive context (Attree, Turner, & Cowell, 2009; Brunswick, Martin, & Marzano, 2010; Wang & Yang, 2011). A complete picture of RD VS skills cannot emerge without investigating these untested domains.

3.2. Age

The literature review includes very few studies of younger RD populations. As Newcombe and Shipley (2014) argued, "Without age-appropriate assessments, we cannot track development, or evaluate the effects of interventions" (p. 14). Only three studies tested VS skills of participants below the age of 7. Most tasks researchers used for groups between 4 and 8 years old were pattern recognition studies, very few used spatial rotation. Without the study of different age groups, a clear picture of the developmental trajectory that VS skills take in growing RDs is impossible. There are also other concerns such as observing and understanding the differences between the transformation of VS skills from childhood, to pre-puberty and to adulthood when interpreting VS developmental skills data (Gilger & Ho, 1989; Petersen, 1979; Waber, 1979).

Researchers need to know the development of VS is subject to sensitive periods of development beyond which compensation would change initial VS abilities.

3.3. Learning vs. Aptitude

The majority of the cited studies in the literature review tested VS performance of RDs, not their cognitive abilities to *learn*. A learning difference for VS skills due to a unique neurology is a logical hypothesis and extension based on what we know to be true about the RD difference in learning to read. Based on their atypical brains, RDs may also learn VS information differently, and they may respond to VS information in a unique fashion compared to nRDs after feedback and training. In the educational curriculum for improving language-based issues in RD, no specific training/feedback program exists to support and improve RD VS abilities because the focus has been on remediating the reading problem. Interestingly, however, the favored and research-based remediation program is a multisensory-structured language program that includes using non-language-based stimuli to enhance reading acquisition (Eden, & Moats, 2002; Joshi, Dahlgren, & Boulware-Gooden, 2002; Oakland, Black, Stanford, Nussbaum, & Balise, 1998). Thus, because Language-based and non-Language-based neurological systems are connected, they may improve together if stimulated by targeted training (Franceschini, Gori, Ruffino, et al. 2013; Gabrieli, & Norton, 2012; Horowitz-Kraus, 2015; Keller et al., 2009; Lorusso, Facoetti, Paganoni, Pezzani, & Molteni, 2006). Future research could implement testing over longer periods of time to observe behavior, strategies, and performance pre- and post-training.

As highlighted in our literature review, people with RD often underperform on non-Language-based executive functions and basic VS tasks (Brosnan et al., 2002; Gilger et al., 2016), visual fields in drawing (Eden, Wood, & Stein, 2003), accuracy in 3D discrimination (Winner et al., 2001), functional coordination of letters in space (Rusiak et al., 2007), and virtual world VS information speed processing (Sigmundsson, 2005). Past studies focused on single time points of performance (e.g., an aptitude test score) and did not consider learning trajectories or responsiveness (Olulade et al., 2012; Gilger et al., 2016). Irrespective of how RDs perform on VS tasks, it remains unknown how they learn VS or respond to VS training.

Earlier we highlighted three studies looking at different forms of learning through practice, for which outcomes were mixed. Two other studies proposed a simple pre/post results observation after practice, which again is different from what we propose here as a training (repeating a skill until it is learned vs. repeating a skill under guidance and feedback to improve and learn new strategies). For example, Nicolson and Fawcett (2000) created a 3D practice study with virtual reality in which RD participants practiced moving a PacMan in a maze to test their VS skill automatizing abilities (i.e., learning a spatial skill and integrating it) compared to controls. The practice helped participants gain normal automatization skills compared to their initial score, but their performance still lagged behind that of controls a year after practice.

Other tests used more dynamic experiments to see how RDs would learn certain strategies to navigate dynamic problems. Attree, et al., (2009) checked spatial recall by having RDs and controls, in a single session, navigate rooms in a veirtual environment (VE) on a screen to find objects, and then remember where the objects were to reconstruct a live floor plan of the layout learned. RDs performed better than controls. Brunswick, et al., (2010) also submerged participants within a VE where they drove around a town and had to pay attention to road signs while remembering to perform certain tasks when they saw these signs. Male RDs spotted targets and reacted faster than all other groups. Sigmundsson (2005) studied a similar situation but this time with auditory indicators of road signs to which participants had to react to by performing some gesture, and found the opposite to be true; individuals with RD were slower. These contrasting results seem to lean toward some types of advantages in RD for basic learning skills as recall of information and problem solving in 3-dimensional spaces, but the data is still too scarce to know whether VS training helps individuals with RD strengthen their visuospatial cognitive abilities, or VS thinking skills, or even transfer those skills to Language-based capacities.

Among the VS practice studies conducted on nRD populations, results show improvement in spatial test performance with neurological effects lasting overtime, and transferring to other cognitive domains (Hötting, Holzschneider, Stenzel, Wolbers, & Röder, 2013; Uttal et al., 2013) in adults and children (Stieff et al., 2014). But we must also be aware that VS training affects some aspects of VS tasks and not others (e.g., improving the speed of rotation alongside a minimal improvement in accuracy) (Kail, Carter, & Pellegrino, 1979; Linn & Petersen, 1985; Uttal et al., 2013). This indicates that studying VS in RD will require much more detailed and complex designs that we have seen so far. That said, Newcombe and Shipley (2014) explained that performance vs. learning ability is important in students' VS skills. Researchers should consider individuals' initial spatial skills differences and the effects these have on the processing and learning of spatial information. If RDs, with their unique neurology, have different VS networks than nRDs, what does that imply regarding their learning abilities in this domain, and how best to teach individuals based on their needs? The reading skill analog is clear: RDs compared to nRDs perform differently on reading tests and learn to read and respond to training differently. Consequently, RD students receive special training to bring and keep them on par with their peers. Current best practices in remediation "normalize" the RD brain, improving the function of left hemisphere reading pathways (Simos et al., 2002; Keller & Just, 2009). How this normalization affects VS learning or aptitude, or other non-reading networks is unknown, although Gilger and colleagues suggest that the ultimate effects of intensive reading interventions may be broader than simply fixing the disability and these effects are age-sensitive (Gilger, Allen, & Castillo, 2016).

In short, VS training is beneficial and is not simply relevant to non-Language-based cognitive domains but benefits other aspects of cognition. These benefits may differ depending on the skills, types of tasks, and age span of participants. Visuospatial training yields positive cognitive developmental changes, and perhaps Language-based skills improvements, but it may need to take place quite early in RD child development. It is unknown how RDs can best benefit from training and avoid passing potential sensitive VS learning periods.

CHAPTER II

Spatial Study

To reiterate, a number of issues were identified in the review of VS processing in RDs vs nRDs: the lack of comprehensive tasks, the absence of studies investigating age trends, and the focus on single-point-in-time measures without a distinction between aptitude vs. learning. These issues prompted this short-term training study to evaluate VS learning outcomes in children and adults with RD. The study was designed to address the three issues mentioned above by using both static and dynamic tasks, across a wide range of age, and looking at both single time performances and learning trends simultaneously.

II.1. Methods

This study evaluates the differential impact of practice and training on spatial cognition for RD and nRDs as a function of age. The study is set up as a 2-factor between-group design with repeated measures, that is two groups (RD and nRD), pre-post design, with 3 training days intervening.

1.1. Recruitment

Participants were recruited via public flyers in town and two college campuses, and through direct contact with schools in Monterey and youth/parent clubs in the Central Valley region. Participants or their parents contacted our lab, were informed about the study and pre-screened for eligibility. Meeting times for 5 days were then scheduled.

Testing was conducted in the lab on campus or at a central location such as our downtown center, and other centers when testing out of town. At the first meeting, informed consent was obtained from parents and adult participants, and informed assent was obtained from minors. At the first session, the adult participants or the parents of minors were also asked to complete questionnaires. Some opted to take the questionnaires home and return them at a later session. Participants were paid at the end of the study.

1.2. Participants

To be admitted into the study, participants had to meet specific exclusionary and inclusionary criteria. The following exclusionary criteria had to be met by both the potential RD and nRDs:

- No history of experiential or environmental factors that would explain an inability to learn to read normally (e.g., deprivation, lack of schooling, trauma, etc.)
- No difficulty speaking and/or reading English due to multilingualism
- No serious psychiatric issues that would interfere with learning or performance
- No gross physical or neurologic condition that would influence cognition or interfere with the performance
- No IQ lower than the average range
- No comorbidity with severe ADD/ADHD, or other disorders that would inhibit learning or prevent functioning in the study

RD Participants

In addition to the exclusionary criteria, participants were identified as potentially in the RD group vis a vis these inclusionary criteria:

- A prior formal diagnosis as dyslexic by a healthcare or school professional.
- The existence of an IEP at the start of the study, or evidence of having had one in some or all of grades 2nd-12th.
- Suspected as RD based on school (e.g., grades), teacher, parent, or others' report, but without a formal diagnosis.

Subsequent to the completion of the study, all potential RD participants had their diagnosis validated by our testing. If our testing (i.e., below normal reading and spelling scores) and the participants' history or inclusionary criteria agreed, the individual was assigned to the RD group for analyses.

nRD Participants

The potential nRD participants had these inclusionary criteria:

- No prior formal diagnosis as dyslexic by a healthcare or school professional.
- No educational support (e.g., extensive tutoring, an IEP, etc.) at the start of the study or evidence of having had such support in some or all of grades 2nd-12th.
- Suspected as normally developing based on school performance, teacher, parent, or other's report.

1.3. Procedures

All participants were seen individually for 5 consecutive sessions (see Table 4). The order and overview of these sessions appears in Table 1 below. The first day (Pre-test) and last day (Post-test) lasted approximately 2 hours each, during which questionnaires were given along with the same IQ, academic achievement, and similar but not identical computerized tests. Days 2 to 4 were training days[3], each lasting for approximately 30-45 minutes, during which participants took part in a series of VS training exercises. During all 5 sessions, participants under 18 were given small tokens (e.g., toys, pens, etc.) as a reward for their work. At the end of the study, participants and parents were debriefed and completed a form to receive payment.

[3] Participants were typically trained alone, or on occasions in groups of 2 to 6 participants separated across the testing area.

Table 4. Week-long Study Sessions Format

Sessions	Procedure	Total work time
1st	Initial meeting & Informed consent	~ 15 mins
	Questionnaires (Biographical information)	~ 15 mins
	Administered by researcher:	
	Play activity questionnaire (ELEQ)	~ 5 mins
	Paper-pencil WASI/WRAT standardized tests (*alone*)	~ 70 mins
	Computerized spatial tasks (*alone*)	~ 35 mins
2nd to 4th	Spatial training *(alone or in groups)*	~ 25-35 mins/visit
5th	Paper-pencil WASI / WRAT standardized tests	~ 60 mins
	Computerized spatial tasks	~ 35 mins
	Debrief discussion on study with participant/parents and Closure	~ 10 mins
Total time across 5 meetings		**~ 320-350 mins (5:20 h to 5:50 h)**

1.1. Tasks and Outcome Dependent Variables

The measurements of this study are shown in Table 3 below (Refer also to 'List of Abbreviations' in introductory pages). In various combinations, these data are used as dependent variables and/or covariates. Given the large number of measures examined in this work, we provide here and in 'List of Abbreviations' a summary of acronyms that will be used throughout this report. The measures are more fully described below.

With the exception of the questionnaires, all psychometric and computer tasks were administrated both at pre-test and after training at post-test.

We also used two *Signal Detection* theory dependent variable measures common to the field of psychology but less to the study of dyslexia which are:

1/ Sensitivity: participants' ability to distinguish noise vs. real signal, in our case distinguishing right answers in a pool of stimuli (non-identical or identical figures, non-rhyming or rhyming words, matching or not matching pieces) (Stanislaw and Todorov, 1999). More will be said on these measures subsequently in the analyses section and discussion.

2/ Decision Threshold: participants' general tendency to respond yes or no, depending on their perceptual threshold. That threshold is the cognitive state at which a participant is detecting a stimulus and is willing to emit a response (Stanislaw and Todorov, 1999).

Parent-Adult Questionnaire

These questionnaires provide data to assess the suspected and diagnosed reading challenges of participants, and help ensure that our diagnosis aligns with personal/family history and educational reports, as well as the educational paths of both the participant and their biological family members (Lefly & Pennington, 2000), activities of choice, talents, overall health, and socio-economic status. A copy of the questionnaire appears in Appendix 1.

Early Life Experiences Questionnaire (ELEQ)

Participants detailed their preferred type of play, hobbies, or activities over the past three years (see Appendix 2). These data yield a summary score 0-150 (on a scale of 1-6 participants indicate how often they have performed a given activity in the past three years) indicating the type of visuospatial practice participants have had. Higher scores reflect more frequent spatial manipulation experience, visual detail experience, and artistic experience, it is also associated with higher frequency of assembly, visualization, design, spatial complex stimuli calculations, and fine motor abilities (Fraser, Bouchard, & Keyes, 1979; Gilger et al., 1989).

Wechsler Abbreviated Scale of Intelligence (WASI)

A commonly used, 30 minutes long clinical, psychoeducational, and research tool assessing cognitive ability in persons aged 6-90 years (Wechsler, 1999). Four subscales are used in this abbreviated IQ scale that assesses both Language-based (Vocabulary & Similarities subscales), and non-Language-based cognitive abilities (Block Design, & Matrix Reasoning subscales). Standardized scoring protocols yield subscale T scores (mean 60, SD 10) and VIQ, PIQ and FSIQ scores with a mean of 100 and SD of 15. Average reliability coefficients for the subtest scores ranged from good (α =.87) to excellent (α =.91) for ages 6 to 16, and from (α =.90) to (α =.92) for ages 17 to 90 on the subtests. Test-retest stability indicates acceptable (.79) to excellent (.90) for ages 6 to 16, and good (.83) to excellent (.94) for ages 17 to 90 on the subtests. Correlations between the full battery WASI-II and the original WASI, WISC-IV, and WAIS-IV are acceptable (0.71) to excellent (0.92). VIQ and PIQ have been shown to differentially correlate with a number of outcomes, including language skills and reading, and spatial skills, respectively.

Table 5. Tasks and Outcome Dependent Measures[4]

Tests	Task	Dependent measures
IQ (WASI)	Verbal Scale (vocabulary & similarities) Non-verbal Scale (block design & matrices)	Standardized Scores for Verbal IQ, Performance IQ and Full Scale IQ
Academic Achievement (WRAT)	Reading Recognition and Spelling	Standardized and age-adjusted reading and spelling scores
Computer Tasks	Pseudo and Real Word Rhyming, Cubes Rotation, Tangram Shapes Assembly, Impossible Figures	Performance/ accuracy raw scores, Hits, False Alarms, Misses and Correct Rejections, Response time in milliseconds, Sensitivity (d'), and a measure of decision threshold (β)
3-Day Training (Task Book and manipulatives)	Tangram, Legos, Windows Test	Performance raw scores, Time to complete in minutes (on each 3 books, and overall)
Early Life Experiences Questionnaire (ELEQ)	25-Questions survey	Frequency of play Spatial activities/hobbies for spatial-related tasks over 3-year span. Summary score for the degree of experience with spatial activities.
Parent-Adult Questionnaires	Questionnaire about self, child, and family	Demographics, Education, Activities, family SES, Health and Disability history, School, Performance History etc.

Wide Range Achievement Test (WRAT)

A frequently used individualized achievement test (15-30 minutes long), measuring the ability to read, comprehend text, spell and solve math problems. For the purpose of this study, only the reading and spelling subscales were used (Jastak & Wilkinson, 1984). The WRAT was

[4] The tests are further described in subsequent sections.

standardized on over 3,000 participants aged 5 to 94, and was highly valid across cultures and cognitive conditions (Chua, Liow, & Yeong, 2016; Sayegh, Arentoft, Thaler, Dean, & Thames, 2014). Test-retest reliability coefficients were strong ranging from .78 to .89 (age-based sample), and from .86 to .90 (grade-based sample). The Reading and Spelling subtests used in this study are standardized by age to have a mean of 100 and SD of 15.

Computerized Pre-Post Tests

All four computerized tests are administered individually. SuperLab 5.0.0 (Abboud, Heller, Matsak, Schultz, & Zeitlin, 1991) was used to design these tasks.

Variation of the Shephard-Metzler Cubes (CUBE). This is a timed non-Language-based dynamic spatial reasoning task (Shepard & Metzler, 1988), that takes roughly 15 minutes to complete. It has 76 items at pre-test and 72 at post-test. The problems viewed are different at pre- and post-test. Participants are required to determine whether two 3-D objects displayed on the screen are the same, or different (mirror opposites). The objects are represented as black-lined stacks of white-cube objects over a white background (see Figure 1). One item of each pair is the standard stimulus (on the left of the screen) and one item is the comparison stimulus (on the right of the screen). The comparison stimuli are presented in different orientations, with no or slight rotation relative to the standard, or in 30-90 degrees of rotation. In roughly half of the trials, the comparison stimuli can be rotated to perfectly match the standard, and in half the trials no degree of rotation will yield a standard match as the comparison stimulus is flipped or mirror-imaged. Two answers are possible for each stimulus pair or trial: the items are either the same (40 items at pre; 36 at post) or different (36 items at both pre & post).

After reading instructions and practicing on 4 sets with the researcher, participants must press one of two keys on a keyboard: 'Y' for YES if the objects are the same, and 'N' for NO if the objects are not the same, even if they are oriented similarly. A new set appears immediately after an answer from the participant. The sets are randomized across participants and they are instructed to respond as quickly as they can without making mistakes. Possible answers are: hits (participants press Y when the objects are indeed the same even if they appear in a different rotated orientation); miss (participants press N when the correct answer was Y); false alarm (participants press Y when the correct answer was N); and, correct rejection (participants press N when the objects are indeed different no matter how they are rotated).

The Shepard-Metzler task has been used widely (Shepard & Metzler, 1971; Vandenberg & Kuse, 1978), with good inter-item Kuder-Richardson reliability (.88), and a test-retest reliability of .83. The task is moderately or highly related to other tests of spatial ability and mental rotations tests, certain math skills and PIQ (Linn & Petersen, 1985; Ozer, 1987). The Shepard-Metzler has also been shown to cause region-specific activation patterns in brain imaging studies that are different from the patterns found during Language-based processing tasks (Cohen, Kosslyn, Breiter, DiGirolamo, Thompson, Anderson, … Belliveau, 1996; O'Boyle, & Benbow, 1990; Olulade et al., 2012; Shepard & Metzler, 1971).

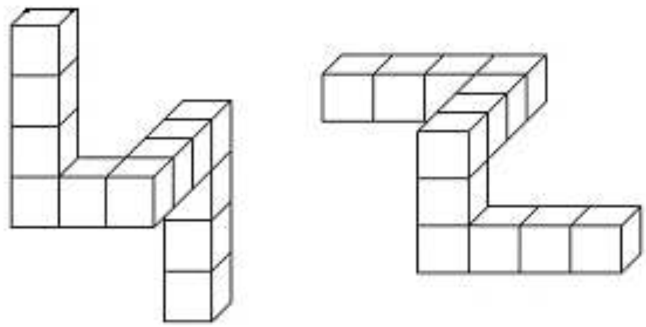


Figure 1. Participants compared and pressed Y (figures are the same despite the rotation), or N (figures are different despite the rotation) on their keyboard. Here the answer is No, the stimuli are mirror opposites.

Variation of the Minnesota Paper Form Board test (Shapes). There are 36 items in this 10-minute long task, similar to the original Paper Form Board (Likert & Quasha, 1941). There are 12 sets of items, each with a black test shape on the right-hand side of a grey screen, along with a comparison set of black pieces on the left that, when combined, may or may not make up the test shape. Each of the 12 stimuli sets is presented randomly three times: once with the comparison pieces separated (4 iterations), once with the pieces rotated (4 iterations), and once with the pieces scrambled (4 iterations). The 12 sets are different at the pre- and post-test (Figure 2).

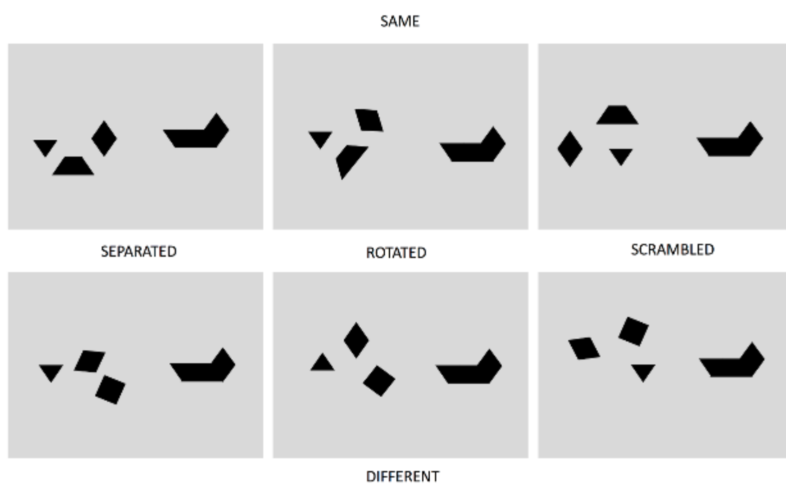


Figure 2. Participants must decide and press Y (the scattered figures can make the shape), or N (the scattered figures cannot make the shape) on their keyboard.

After reading instructions and practicing on 4 stimulus sets with the researcher, participants must press one of two keys on a keyboard: 'Y' for YES if the pieces can come together to match the whole shape on the right (18 sets); and 'N' for NO if the pieces cannot come together to match the whole shape on the right (18 sets). A new set appears immediately after an answer from the participant. The sets are randomized across participants and participants are told to respond as quickly as they can, but to also minimize mistakes. Possible answers are: hits (participants press Y when the pieces can be combined to create the test figure); miss (participants press N when the correct answer was Y); false alarm (participants press Y when the correct answer was N); and, correct rejection (participants press N correctly indicating that the pieces do not make-up the test figure). In Quasha, and Likert (1937), two versions of the Minnesota Paper Form Board test were compared, the lowest corrected correlation was .94, and the interform r was .85. Roszkowski (2001) reported a test-retest reliability of .71 to .85, and internal consistency coefficients of .93 to .95 for half forms and .86 to .91 for alternate forms. This test has been correlated to spatial abilities or abilities to manipulate objects in space, in professionals such as artists and designers (Mackie, 2005; Likert & Quasha, 1995).

Word Rhyming Task (Rhyming). This is a timed - rhyme judgment task in which participants determine if two black words, presented mid-screen on a white background, rhyme. This task taps into word decoding and phonological processing, and has been shown to discriminate between dyslexics and non-dyslexics in a variety of studies (Olulade et al., 2012; Pugh et al., 2000). These types of tasks typically activate the frontal, the left hemispheric occipital and parietal temporal regions containing language processing centers such as the Brocca, Wernicke and angular gyrus (Olulade et al., 2012). This is in contrast to regions activated during non-Language-based visuospatial tasks, reported to either overlap with the previously cited areas along the left frontal gyri, occipital, and parietal regions, or be processed directly within opposite left hemispheric regions (Vogel, Bowers, & Vogel, 2003). In each trial, participants press keyboard keys as quickly as they can (‘Y’ for YES, ‘N’ for NO), indicating whether the two real words (e.g., carbon and prison) or two non-words (e.g., tigid and ligim) rhyme. Possible answers are: hits (participants press Y when the words rhyme – 60 pairs); miss (participants press N when the correct answer was Y); false alarm (participants press Y when the correct answer was N); and, correct rejection (participants press N when the words do not rhyme – 60 pairs).

The pre- and post-tests each contains 120 sets of two-word items to compare. Half are real words and half are non-words. A new set appears immediately after an answer from the participant. The sets are randomized across participants. Word rhyming tasks have been assessed in Yopp (1988) where reliability was found at α=.76. Other articles report more or less higher indices such as Gathercole, Alloway, Willis, & Adams, (2006) reporting a test-retest reliability between .84 and .90 for rhyming tasks in 6 to 11-year-olds (see also Frederickson, Frith, & Reason, 1997 for test types).

3-Dimensional Impossible Solids (3DIS). 3DIS is considered a holistic visuospatial comprehension and reasoning test (Schacter, Cooper, & Delaney, 1990). This is a 15 minutes long task, comprised of a series of 3-dimensional solids, half of which have been drawn in a way that makes them impossible to exist in a normal 3-dimensional space. There are 60 black-lined solids (30 are possible to exist in 3 dimensions, 30 are misshaped and cannot exist in three dimensions), placed at the center of a white screen. Solids are randomized across participants. The level of difficulty has been varied with 18 easy solids and 18 hard solids (Figure 3).

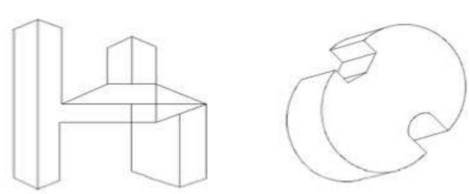


Figure 3. Participants must decide and press Y (the solids can exist in 3D) or N (the solids cannot exist in 3D) on their keyboard. Only one figure per screen presentation.

Participants are required to press 'Y' (the figure is not impossible or could exist in normal space) or N (the figure is impossible and could not exist in normal space) on the keyboard as fast as they could. A blank screen appears for one second between each presented figure so as to avoid automatic responses from participants. Eight practice and instructional items appear before the actual test is started. Possible answers are: hits (participants press 'Y' when the objects are possible in normal space – 30 solids); miss (participants press 'N' when the correct answer was Y); false alarm (participants press 'Y' when the correct answer was N); and, correct rejection (participants press N when the objects could not exist in normal space – 30 solids).

The 3DIS task has been used in a number of studies looking at spatial cognition. It has been shown to be correlated with visuospatial talent, has been used as a tool in studying implicit memory, infants' visual preferences, autism, gender differences and much more (Chan, 2010; Williams & Tarr, 1997; Winner et al., 2001). It also is one of the few spatial tasks with suggestive evidence that dyslexics may outperform nondyslexics, particularly in speed, when discriminating these solids in space (Diehl et al., 2014; von Károlyi & Winner, 2005; Von Károlyi et al., 2003; Winner et al., 2001).

Training Booklet

Validity and Rationale for Training Booklet. Some elements integrated into the training tasks have been used in other research. However, we found no multisensory approach study designed using manipulatives concomitantly with these tasks, much less in the RD context. There is, however, some evidence that hands-on practice enhances performance in VS learning and problem-solving contexts (Cass, Cates, Smith, & Jackson, 2003; Zacharia & Olympiou, 2011), and Young RDs have been shown to be particularly responsive to reading remediation programs that use multisensory approaches (Eden, & Moats, 2002; Joshi, Dahlgren, & Boulware-Gooden, 2002; Oakland, Black, Stanford, Nussbaum, & Balise, 1998).

Uttal et al. (2013) have gathered a tremendous amount of research highlighting the beneficial effects of training in non-Language-based areas. Good performance in this domain was positively associated with academic achievement. The studies reviewed by Uttal et al. (2013) were done in various contexts and ages ranging from elementary school to college and engineering programs, as well as professional contexts. Results showed that these trainings not only improved learning abilities but also problem-solving strategies more generally. They also improved the understanding of spatial information with the acquired skills transfer to other tasks (see also: Hartman, Connolly, Gilger, Bertoline, & Heisler, 2006; Vakil, Lowe, & Goldfus, 2015).

Based on these and other findings, we have built a VS training program with the following characteristics: 1. brief in format, taking but 30-45 minutes per session; 2. portable with prepared booklets and accompanying materials that can be moved readily place-to-place; and 3. a program based on research that suggests such paper-and-pencil practice and instruction works, and that the inclusion of hands-on models and manipulatives may increase the effect even more (perhaps especially for RDs).

A validity check on the effectiveness of the training will include: whether or not there is pre/post-test improvement on the computerized tasks beyond expected practice effects; time to complete training books across 3 sessions with speed expected to improve; and an increase in workbook accuracy across problems and training sessions.

Tangram Training. Tangram tasks have been used in research on attention (Owens, 1998) to facilitate problem-solving. Lowery and Knirk (1982) looked at visualization and learning and used tangrams to assess students increased performance on spatial tests. Thus, this task was considered specifically appropriate for our study.

There were 6 exercises in this category. The Tangram problems were constructed to mirror but not duplicate the skills needed to solve the computerized Shapes task, with an added manipulative component. First, the researcher completed two practice problems with the participants, showing what is expected, and gave feedback on how to solve the problems. Answers were worked out with the participants until the researcher was assured that the task was understood. In the first task, participants were asked to pull several shapes out of a set of 6 flat plastic tangram shapes, numbered from 1 to 6. Pictures on the page showed which manipulatives to pull and arrange on the table to work with (picture a.). Participants solved 6 problems. Once they placed the shapes together in a whole (picture c.) to match the target shape (picture b.), they drew in the empty shape (picture d.) what they had in front of them with lines and numbers (picture e.). Once the 6 problems were completed, the researcher reviewed each problem with the participants, showing the solutions, and reworking the problems that were incorrectly solved. For each of the three training days, Tangram accuracy scores are obtained: the number of correctly solved problems and time to complete the Tangram portion of the booklet. Analyses also included a tracking of progress on Tangrams average accuracy across the three booklets.

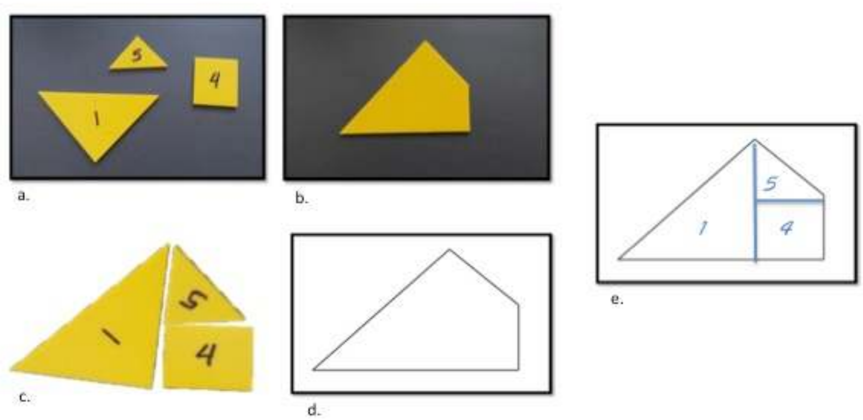


Figure 4. a, b, c, d, e. Example of a Tangram problem (participants also manipulated these shapes in their hands to solve the problem).

Lego Towers Matching. Denes Cappelletti, Zilli, and colleagues (2000) used what they call a “Lego position discrimination task” in which they presented Lego blocks in different positions to assess individuals’ ability to discriminate changes in spatial configuration. This task seemed to be well responded to and was a valid tool to discriminate the differences in cognitive abilities between controls and people with spatial location difficulties which has been one of the issues highlighted in research on dyslexia. Such Lego tasks were also used in studying gender differences in visuospatial abilities, and in assessing mathematical abilities in young.

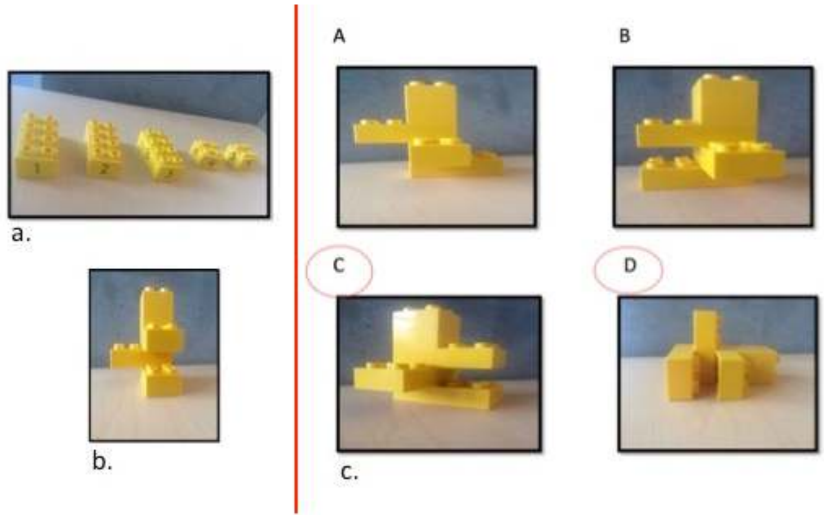


Figure 5. Lego towers to build and then discriminate against four options (the two circled are correct).

Researchers practiced on two problems with the participant. The task consisted of building a tower out of 6 numbered Legos (Figure 6.a.). Participants had to take out the indicated Legos from their set, build a tower according to a picture (Figure 6.b.). Once the tower was built, participants had to choose out of 4 pictures which two were identical to the tower they had built (Figure 6.c.). Once the 6 problems were completed, the researcher went over the answers with the participants and practiced again on the problems missed pointing out to solving strategies. This task taps into skills similar, but not identical, to the Cubes computerized task with an added manipulative component. For each of the three training days, Lego accuracy scores are obtained: the number of correctly solved problems and time to complete the Lego portion of the booklet. Analyses also included a tracking of progress on Lego average accuracy across the three booklets.

The Windows Test (WT). In the literature review provided at the beginning of this work, spatial rotation was found to be one of the most used tasks for assessing RD's VS abilities and was a task in which they performed generally lower than NRDs. In our review, no study was found using this windows test, thus the addition of this task provides new insight into RD's mental rotation capacities on a different type of rotation. The WT is based on the Mental Rotation subtest of the Cognitive Modifiability Battery (CMB). It was used to assess and increase cognitive non-Language-based flexibility in young individuals (Tzuriel, 2000; Tzuriel & Egozi, 2010). Tzuriel and his colleagues did show significant changes in cognitive processing and modifiability pre/post intervention, using this type of tasks, and a higher improvement in disadvantaged participants with learning disabilities than for controls (Tzuriel, 2000). He also contends that the post-test information is much more indicative of intellectual ability than the pre-test performance which is of particular interest to this study's hypotheses. In Tzuriel and Egozi (2010), the reliability of the WT gave a Cronbach alpha reliability of .79, and a test equivalency reliability of .82. There was a clear linear degree of decrease in performance as the complexity of rotation increased and symmetry changed. The training was found to improve spatial performance.

In this last task, instructions are given to the participant and then two example problems are presented. Afterward, participants are presented with 3 pages composed of two columns of 5 small houses each (15 problems total). Each house contains 6 squared windows each, and a white roof.

The left column contains houses with closed windows, the right column contains empty houses to draw on (Fig. 6). The first set of 5 houses is rotated at 45 degrees, the second set at 90, and the last at 180 degrees. Each house contains different positions of closed windows, which also varies to increase difficulty (2, 3, & 4 windows closed).

Figure 6. Windows Test (based on the Mental Rotation subtest of the Cognitive Modifiability Battery (CMB) - (Tzuriel, 1995, 2000a, 2000b; Tzuriel & Egozi, 2006, 2010).

Participant must shadow in the exact same windows on the right column as the corresponding houses in the left column. The researcher ensured that the participant understood the principle and left the participant to work on the three pages. Once the participants completed the three pages, the researcher went over the answers and reviewed with the participant the incorrect answers. Feedback was given about how to understand rotation and mirroring effects in the task. This task provided practice in visual-spatial rotation and perception. For each of the three training days, WT accuracy scores are obtained: the number of correctly solved problems and time to complete this portion of the booklet. Analyses also included a tracking of progress on windows average accuracy across the three booklets.

Debriefing

A form with a summary of the study and the research teams' contact information is given. The researcher summarizes the underlying goals of the study and enquires if the participants and/or their parents have any questions. Participants are then reminded of the timeline to receive their financial compensation and given a copy of their consent forms.

1.1. Independent Variables

The primary analysis is pre-to-post effects on the computerized and psychometric measures, and if these effects are different for RD and NRD groups as a function of age. Additional exploratory analyses may include other variables such as responsiveness to training (e.g., time to complete booklets), preferred problem-solving strategies by group/gender/age, and items from the questionnaires (e.g., play habits, abilities, and hobbies).

II.2. Hypotheses

2.1. Hypothesis 1: Language-Based Performance Comparisons

Baseline Theoretical Predictions: How will individuals with RD perform on language-based tasks relative to developmentally normal peers at baseline (pretest)?

- RD and nRD participants will perform similarly on the Full-Scale IQ, although RDs may be slightly lower in the VIQ scale.

- RDs will show significantly lower performance on the WRAT spelling and reading tests.
- RDs will perform significantly lower than nRDs on the computerized Rhyming task.
- RDs and nRDs may differ in their sensitivity to stimuli changes and decision threshold for the LB computerized tasks. RDs might have lower sensitivity since this index is related to accuracy. In the case of decision threshold, no research allows making a clear conjecture for either group.
- We have unclear predictions about the effect of age on LB performances, although there is some expectation that younger subjects will perform differently than older subjects.

Post-training theoretical Predictions: How will individuals with RD perform on language-based tasks relative to developmentally normal peers after at post-test, and will they differ in the magnitude of their scores change from pre to post-test? Will these effects be also age-dependent?

- Some improvement is expected on post-test scores, on most tasks, partly due to a repeated measures effect. Language-based performance (VIQ, WRAT subtests, and computerized Rhyming task) may increase for both groups, although RDs should still exhibit lower scores relative to nRDs on these measures.
- Language-based performances will improve slightly pre to post-training for the RD group showing a slight learning effect.
- There might be a learning trend differences between RDs and nRDs in the younger samples, with young RDs showing only marginally similar or higher change magnitude (learning). There may be RD/nRD differences in learning in the older ages as well with older RDs being lower in their learning index than older nRDs (Newcombe & Shipley, 2014). In their sensitivity to stimuli changes and decision threshold, age may also matter. Young RDs might have lower sensitivity and decision threshold.

2.2. Hypothesis 2: Visuospatial Performance Comparisons

Baseline Theoretical Predictions: How will individuals with RD perform on visuospatial tasks relative to developmentally normal peers at baseline (pretest)?

- At baseline, no significant difference in spatial skills is expected (Gilger et al., 2016), although there may be a slightly better performance on 3DIS for RD participants.
- In their sensitivity to stimuli changes and decision thresholds on VS computerized tasks, RDs and nRDs should differ. RDs might have lower sensitivity since this index is related to accuracy. In the case of decision threshold, no research allows making a clear conjecture for either group.
- There is no clear prediction for variability by age, although there is some expectation that younger subjects will perform differently than older subjects, perhaps exhibit more difficulty with the problems given.

Post-training theoretical Predictions: How will individuals with RD perform visuospatial tasks relative to developmentally normal peers after training (post-test), and will they differ in the magnitude of their scores change from pre to post-test? Will these effects be also age-dependent?

- Improvement is expected on most tasks in part due to a repeated measures effect, predictions are less clear as to actual (PIQ, CUBE/SHAPE/3DIS accuracy, response time, sensitivity and decision threshold) scores improvements based on the sole effect of the 3-day VS training. Both groups may improve but more so for the RD group if indeed they are more responsive to VS information.
- RDs will exhibit a greater learning effect relative to baseline (steeper and larger improvement in VS) and relative to controls.

- There might be a learning trend difference between RDs and nRDs in the younger samples, with young RDs showing the greatest response to training. There may be little or no RD/nRD difference in learning in the older ages (Newcombe & Shipley, 2014). In their sensitivity to stimuli changes and decision threshold, age may also matter. Young RDs might have lower sensitivity and decision threshold in VS tasks, compared to all other groups.

2.3. Hypothesis 3: Groups' Learning Behavior During Training

Is there a different learning pattern between RD and nRD in their VS training outcomes? Theoretical Prediction: No research has used manipulatives such as used in this design, thus we cannot compare our results to previous studies in that domain. The effect of manipulatives will need to be explored in future research. That being said, if general beliefs about RD VS abilities were verified we would expect them to perform better and perhaps faster in the three booklets training tasks given. However, our literature review has shown a different perspective. Thus, RDs are expected to perform quite similarly or worse than their counterparts generally, but also more specifically, these results should be task-dependent. We cannot also separate the developmental age trajectories attached to being RD or not, which should mediate the VS performance outcome obtained as addressed in the previous hypothesis. As such, the RD group should perform either similarly or worse (accuracy and RT alike), depending on tasks, but their results at the third session might show a higher gain in score than nRD given that the training may be an activity that evokes less conservative thresholds for their non-Language-based cognitive process than in the Language-based tasks.

CHAPTER III

Results Analyses

Analyses were conducted using SPSS, Version 24 (IBM® SPSS® Statistics, 1989). General means comparisons and ANOVAs were used for statistical analyses. Depending on the analysis, tests were one- or two-tailed, with descriptive statistics and results including effect sizes (Cohen, 1990) and tests of assumptions. The measurement indices or dependent/independent variables obtained in this study are summarized in Chapter 2 above. Below are summaries of the essential analyses using these indices under each of the study's specific hypotheses.

For some analyses, participants were categorized as falling into one of four groups: Young RDs (7 to 12 years old), older RDs (13 to 24 years old), young nRDs (7 to 12 years old), and older nRDs (13 to 24 years old).

III.1. Sample

The complete sample consisted of a total of 90 participants. Sixteen participants were eliminated from the final sample based on two criteria: 1/their consistent positions as extreme outliers compared to the overall sample on their standardized IQ (below 74 and above 147) (n=8); 2/ based on their missing data (n=8). A total of 74 participants were retained after data cleaning. Ages ranged from 7 to 23 for RDs (*M*=11.55), and 7 to 24 for nRDs (*M*=12.84). Participants 18 years old and above were from a four-year university, and younger participants were from regional schools, specialized centers, and youth recreational centers.

Table 6. Demographic breakdown.

Group	Female	Male	TOTAL	Mean Age	Avg. Family Income	Ethnicity	*n*
Young RD	13	9	22	9.3	99,000	Caucasian	38
Older RD	13	10	23	15.1		Black	1
Young nRD	12	2	14	9.5	124,000	Hispanic	14
Older nRD	6	9	15	18.0		Asian	4
						Mixed race	4
Total *n*			74			(n=61, missing =13)	

III.2. Main measures

Our main measures were all computed based on the four possible answers participants could make: HIT, Correct Rejection, Miss, False Alarm. Thus, Accuracy was calculated as the average of HIT accuracy and Correct Rejections accuracy; Response Time was calculated as the average of HIT RT and Correct Rejections RT. The next two measures are detailed below.

Signal Detection Theory

Computations were performed to evaluate underlying relationships between hits, misses, false alarms, correct rejections and group abilities (Altman, Khislavsky, Coverdale, & Gilger, 2016; Ho, Gilger, & Brink, 1986; Swets, 1964). The accuracy data for the 4 computerized tasks was used to synthesize sensitivity (d') and decision threshold (β) indices based on the methods of Signal Detection outlined in Swets (1964). Preliminary analyses showed that β and d' were not correlated, save for a few sub-measures of CUBE and 3DIS tasks for which the relationship direction was the higher the sensitivity, the lower the threshold, or the higher the threshold the lower the sensitivity (see Table 22, Appendix 3). This indicates that in this particular sample, being sensitive to stimuli change did not equate with being highly stringent or cautious in decision behavior. This is at first glance surprising, however, we ran the same correlations controlling for RD/nRD and the few significant correlations previously found disappeared. Further analyses as described in further sections show that the RD group was quite inconsistent in this sensitivity/decision threshold dynamic, which must have driven these bi-directionally opposite findings.

D-prime (equation 1) is a statistic that summarizes the subject's sensitivity to detect differences between stimuli (Altman et al., 2016; Ho et al., 1986). A higher *d'* score indicates better or greater sensitivity, often translating into low false alarms and misses, and high hits and correct rejections.

$$d' = z \text{ HITs} - z \text{ FA} \tag{1}$$

Beta (equation 2) estimates the subject's decision threshold, or strategy/lack thereof when making judgments about the similarity of stimuli and in deciding how to act upon that decision. A large β suggests a high stringent judgment criterion or threshold. Depending on the context, a higher or lower bias is preferable. For example in war conditions, a low threshold for deciding that a stimulus is detected is needed to detect the most minimal threats, whereas in a situation where there is a lot of noise data, a high threshold before responding to a stimulus is detected is needed to avoid wasting time on false alarms. Our study is quite exploratory in this domain, thus there is no specific expectation, but perhaps it could be optimum for RDs to show high sensitivity (high HITS and Correct Rejections, and low False Alarms and Misses), and high or moderate decision threshold indicating cautiousness and thus deeper cognitive computations, especially in the VS tasks.

$$\beta = \frac{exp((z \text{ FA})^2 - (z \text{ HITs})^2)}{2} \tag{2}$$

III.3. Analyses Results

Analyses were conducted in several phases. Recall that we are interested in the overarching question of improvement at post-test due to VS training. Thus we created a change score calculated on the basis of pre-test scores subtracted from post-test scores. In addition to our RD/nRD groups, we also included a grouping variable for age in order to explore our proposition that age effects will be present. Thus, the primary analyses used 2 (RD-nRD) x 2 (younger-older age) ANOVAs, with raw means scores or means of change scores as the dependent variable. This allowed us to test for the main effects of reading status and age, as well as AGE*Group interactions.

For preliminary comparisons, Table 6 outlines the sample's demographic information and all the means at pre and post-test on every task (IQ/WRAT & WORD/NonWORD, CUBE, SHAPE, and 3DIS). All other measures, (Accuracy, Response Time, Sensitivity (*d'*), and Decision Threshold (Beta)) are in Tables 7 thru 24.

Preliminary analyses revealed that some outliers were polarizing the data set. Outliers were extracted by means of creating z-scores and tagging all score values beyond ±2.0 as outliers. Notable is that beyond half of the outliers were RD, a majority were young RDs. This may be an indication of young RDs' cognitive uniqueness, but this will be addressed in further sections.

3.1. RD/nRD Comparison on LB tasks. Hypothesis 1: RDs will show lower performance on LB measures compared to nRDs.

We first conducted LB performance analyses as a proxy to establish the profile of our groups in which we expected the RD group to show challenges with written/spelling based tasks.

Baseline Performance

IQ & WRAT: The RD and nRD groups differed significantly in their performance for FSIQ: ($F(1,72)= 3.975$, $p=.050$), and VIQ: ($F(1,72)=4.819$, $p=.031$), as well as in WRAT reading ($F(3,69)=5.316$, $p=.002$), and WRAT spelling composites: ($F(3,69)=7.050$, $p=.000$). RDs performed lower than their counterparts in all these measures (see Tables 7&8). The slightly lower FSIQ likely reflects the lower VIQ in the RD sample. This is commonly found in studies looking at RD-nRD comparisons. Commonly, RD-nRD groups are considered cognitively equivalent if they are matched on PIQ, as they appear to be in our sample.

Accuracy: The groups differed significantly on their accuracy for the Word ($F(1,69) = 14.134$, $p=.000$), and NonWord Rhyming tasks ($F(1,69)=8.250$, $p=.000$). RDs had lower accuracy scores overall (Table 9).

Response Time: The groups differed significantly on their response time on the Word Rhyming task ($F(1,66) = 9.170$, $p=.000$), and NonWord Rhyming task ($F(1,65) = 3.332$, $p=.025$). RDs were statistically significantly slower to respond in these two measures (mean Table 10).

***d'*:** The groups differed significantly in their sensitivity to stimuli change on the Word rhyming task ($F(1,69) = 12.994$, $p=.000$), and NonWORD Rhyming task ($F(1,69) = 9.557$, $p=.000$). RDs were overall less sensitive in the detection of rhyming pairs (mean Table 11).

β: There were no significant decision threshold mean differences between RDs and nRDs on any of the LB tasks. However, the data show that the RD group had a lower overall Pre-training decision threshold (see Table 12).

One important question that surfaced as we implemented analyses was the question of the connection between accuracy and speed of response. Indeed one may decrease in time to accomplish a task but also become less accurate and more prone to error, which in this case would not constitute real progress at post-test. We correlated both measures to assess the strength of these relationships (Appendix 3 Tables 23 & 24). Results show that at pre-test WORD/NonWORD accuracy and RT outcomes were not correlated. Also, though non-significant, we see that the more accurate participants were, the slower they were.

Summary. RDs performed generally lower than nRDs on all the LB measures (WRAT and rhyming). This was expected based on prior literature. At baseline RD and nRD groups were adequately matched for IQ, age, and sex. The VIQ RD-nRD difference was expected, and VIQ performance tends to also lower FSIQs for the RD group. There were no specific expectations as to the decision threshold behavior of RDs, and they did not significantly differ on this measure compared to nRDs.

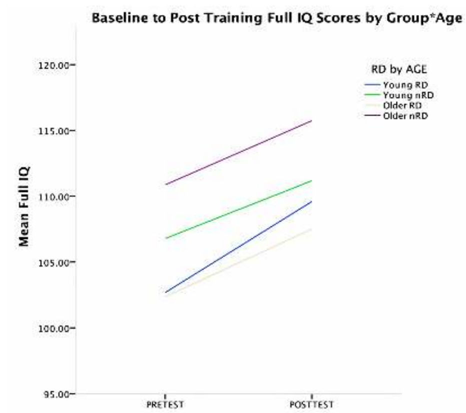
LB Scores Change Magnitude

Analyses were conducted on FSIQ, VIQ, WRAT Reading and Spelling, RT, Accuracy, d', and β for WORD, and NonWORD tasks. Univariate 2x2 ANOVA mean comparisons were used to test for pre to post change scores (post minus pre scores) and the effects of age and group (Overall results and significance are indicated in Table 14 below). There were two groups (RD-nRD) clustered into two levels of age (children as <12, and older participants > 12), yielding 4 age groupings in the test of Group x Age interactions: RD <= 12, RD > 12, nRD <= 12, and nRD > 12.

IQ Change

RDs at post-test still performed worse (as in baseline results) than their nRD peers, consistently (Table 7), however these differences were not statistically significant. However, although non-significant, notice in the main effect of Figure 7a. that the amount of change in FIQ is larger in the RD group on average, especially with the young RDs who show the most difference in that pre to post-training change. There is an age*group interaction between young and older RDs in the Verbal IQ task (Figure 7b.), with older RDs showing a higher posttest mean.

a.



b.

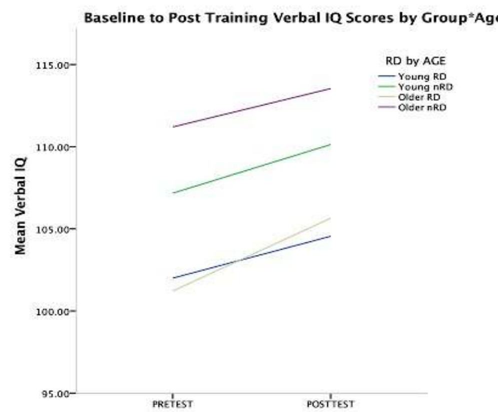


Figure 7. Participants' Full scale IQ (a.), and Verbal IQ (b.), from baseline (Pretest) to after training (Posttest). A higher score is an advantage.

Looking at change scores magnitude, we found a difference, albeit non-statistically significant, in post-training change magnitude (Table 13). The groups did not differ significantly in their FIQ or VIQ change scores after training (note: FIQ is a language-based/non-language-based IQs composite), although, RDs showed the largest change magnitude, where Young RDs had the largest FIQ change, and Older RDs had the largest VIQ change.

Overall, the result suggests that RDs did not significantly improve in performance overall, and beyond nRDs. However they showed a stronger change slope, which indicates a stronger response to the week-long intervention on their overall IQ. In the scope of this study, at this point we cannot parse out what of typical regression to the mean, and actual treatment effect contribute to the variance in these findings.

Table 7. Means of All IQ Tasks by Measures, Age, and Group.

Measure	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
IQ	Pre FIQ	102.68	11.71	22	106.78	15.81	23	102.36	11.31	14	110.87	9.33	15	0.192
	Post FIQ	109.59	12.49	22	111.17	14.79	23	107.5	11.43	14	115.73	8.18	15	0.316
	Pre VIQ	102.00	13.170	22	107.17	17.38	23	101.21	12.50	14	111.20	9.73	15	0.148
	Post VIQ	104.54	15.90	22	110.13	14.12	23	105.64	13.57	14	113.53	7.64	15	0.192

Note: *p* is an index of all between groups significance levels from *F* statistics from ANOVAs. ** p<.001, *p<.05.

Table 8. Means of Academic Achievement Tasks by Measures, Age, and Group.

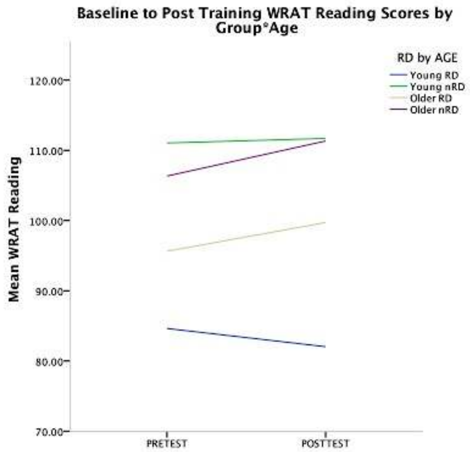
Measure	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
WRAT	Pre WRAT Read	84.64	7.93	22	111.04	15.71	23	95.64	13.54	14	106.33	10.35	15	0.000**
	Post WRAT Read	82.04	9.16	22	111.70	16.90	23	99.71	19.51	14	111.33	12.77	15	0.000**
	Pre WRAT Spell	77.36	6.18	22	104.21	10.92	23	86.5	11.61	14	105.73	16.20	15	0.000**
	Post WRAT Spell	78.27	9.83	22	104.56	9.73	23	86.36	12.66	14	106.14	11.84	15	0.000**

Note: *p* is an index of all between groups significance levels from *F* statistics from ANOVAs. ** p<.001, *p<.05.

Academic Achievement Change Magnitude

RDs did not show improvement at posttest, they performed the lowest in both WRAT tasks at posttest as well (Table 8). Table 8 shows that all these differences were statistically significant. Compared to their baseline scores, RDs show more substantial change in Reading than in Spelling (Figures 8a., b.), which is consistent with our expectation that their might be some attenuated changes at posttest, without dramatic increase.

a.



b.

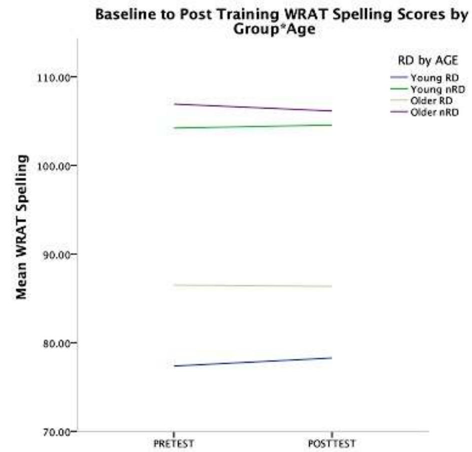


Figure 8. Participants Reading (a.) and Spelling (b.) Academic Achievement scores from baseline (Pretest) to after training (Posttest). A higher score is an advantage.

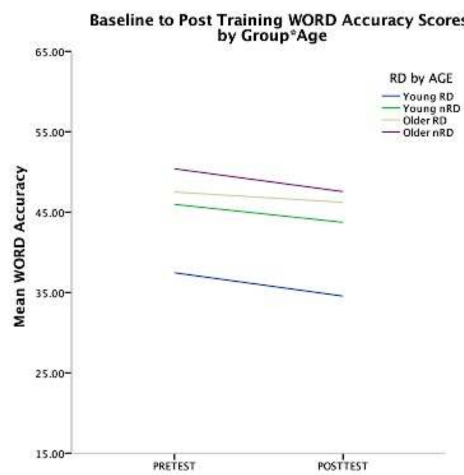
Looking at change scores, there was no significant difference in the magnitude of change between both treatments, between groups in their WRAT Reading or Spelling change scores (except Age being very marginal in the WORD task *p*=.078 – see Table 13). The RD group however, showed the largest positive change magnitude (Table 25).

Thus as in VIQ and FIQ results, we see a specific, wider, response of RDs still without surpassing the performance of nRDs overall.

LB Accuracy Change Magnitude

There was a significant main effect of age on the NonWORD task ($F(1,69)=6.800$, $p=.011$). Table 9 shows that all mean differences were statistically significant, and RDs were overall on average lower in their accuracy on both WORD and NonWORD tasks.

a.



b.

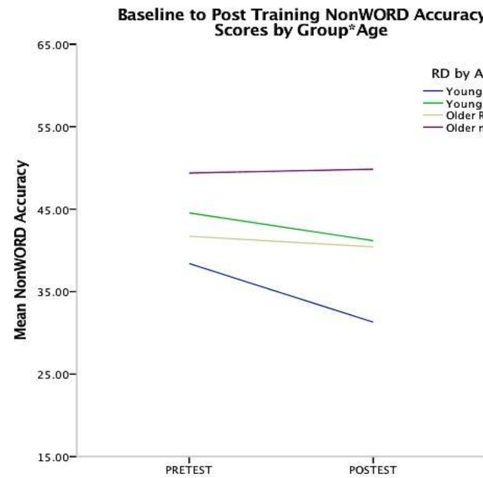


Figure 9. Participants language-based WORD (a.), and NonWORD (b.) accuracy scores from baseline (Pretest) to after training (Posttest). Accuracy is computed on the basis of the averaged composite of Hits and Correct Rejections. A higher score is an advantage.

As seen in Figure 9 and detailed in Table 25 (Appendix 5), RDs have on average smaller change scores in accuracy, with decrease at posttest (however, all groups did show much less improvement in both these tasks).

Overall, the results show a substantial effect of age on WORD and NonWORD performances, and an RD group struggling more to find correct rhyming pairs in either tasks.

Table 9. Means of All Computer WORD and NonWORD Accuracy Tasks Scores by Measures, Age, and Group.

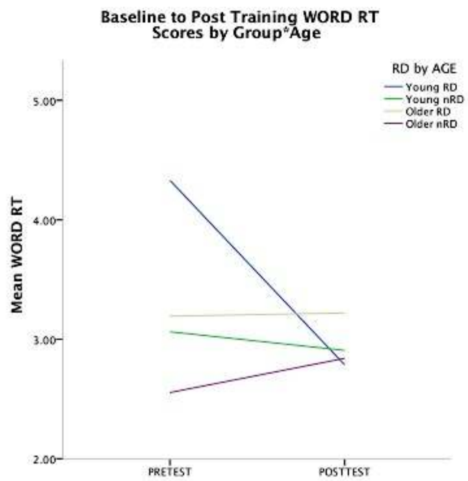
Meas.	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
Accu.	Pre WORD	37.450	5.404	20	45.955	6.615	22	47.500	5.997	14	50.385	6.678	13	0.000**
	Post WORD	34.550	4.751	20	44.217	9.448	23	46.214	6.253	14	47.929	7.770	14	0.000**
	Pre Non WORD	38.400	5.443	20	44.545	6.843	22	41.714	7.226	14	49.385	6.292	13	0.000**
	Post Non WORD	31.300	8.548	20	40.217	10.225	23	40.429	9.002	14	48.429	8.318	14	0.000**

Note: *p* is an index of all between groups significance levels *F* statistics from ANOVAs. ** p<.001, *p<.05.

LB Response Time Change Magnitude

Table 10 shows that the groups differed significantly in their Pretest Response Times, this was no more the case at posttest. Young RDs were faster at post-test in both tasks, with a dramatic timing decrease from being the slowest to the fastest. Older RDs were slower and remained so at posttest. Figures 10a., and b. both show extended interactions and main effects of group and age, quite similarly, where RDs have a higher change magnitudes, and a wider difference between young RD/nRDs. This is interesting as it may indicate that RDs slowed down at post-test, which could be a sign of attention increase in problem solving for that group. Notice (Figure 10) that there was a stronger decrease of time in the younger group than older subjects, which could suggest a tradeoff between feeling more confident with the task for the young, and perhaps taking more time to think for the older group.

a.



b.

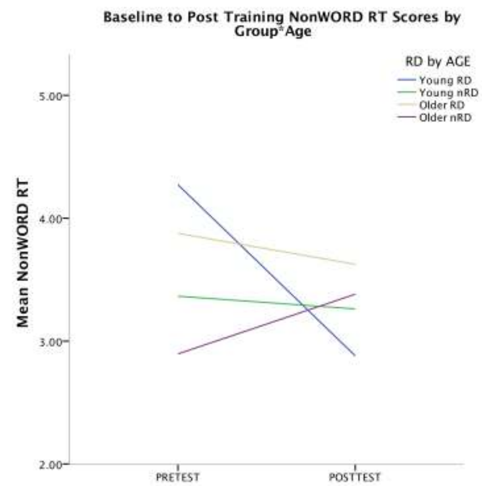


Figure 10. Participants WORD (a.) and NonWORD (b.) language-based Response Time scores from baseline (Pretest) to after training (Posttest). Response Time is computed on the basis of averaged total Hits and Correct Rejections. A lower score is an advantage.

We looked at change magnitude (post – pre test scores), and the groups differed also. Statistically significant differences were noticed. For the WORD task (Group: $F(1,64)=6.862$, $p=.011$; Age: $F(1,64)= 10.221$, $p=.002$; marginally Group*Age: $F(1,69)=3.210$, $p=.078$). For the NonWORD task (Group: $F(1,61)=6.789$, $p=.012$; Age: $F(1,61)=4.945$, $p=.030$; Group*Age: non-significant). Table 25 shows that RDs had the largest change (in a downward direction), with Young RDs showing the

Table 10. Means of All Computer Language-Based RT Scores by Measures, Age, and Group.

Meas.	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
RT	Pre WORD	4.476	1.388	19	3.063	0.988	21	3.193	1.127	13	2.554	0.801	13	0.000**
	Post WORD	3.116	1.634	19	2.893	1.562	22	3.225	1.247	14	2.785	1.504	14	0.846
	Pre Non WORD	4.341	1.742	17	3.366	1.133	21	3.864	1.262	14	2.896	1.077	13	0.025**
	Post Non WORD	3.326	2.048	19	3.256	1.555	22	3.625	1.801	13	3.251	1.820	14	0.939

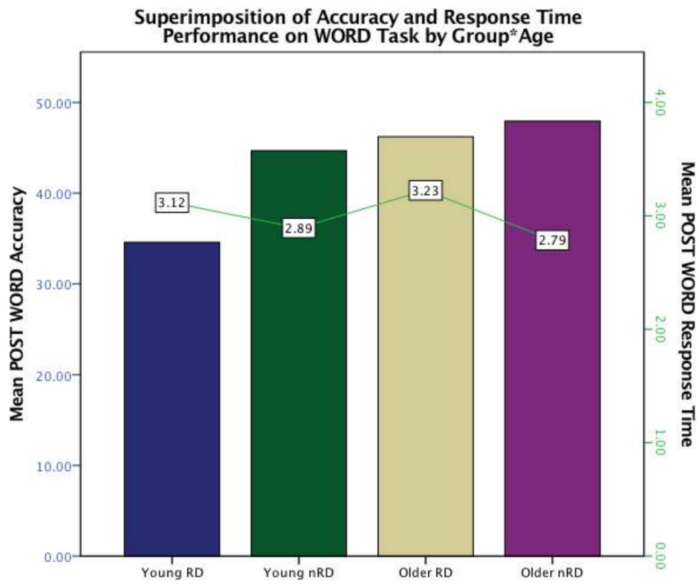
Note: *p* is an index of all between groups significance levels *F* statistics from ANOVAs. ** $p<.001$, *$p<.05$.

widest change.

Tying it Together

Below are charts in which purpose is to bring together accuracy and response time to get a better sense of performance. Research has shown very controversial debates about considering RT without other indices when it comes to assessing performance. We decided to include accuracy, and also signal detection indices to get a more complete picture of RDs' cognitive processes. The Left axis represents Accuracy (colored boxes), and the right axis represents RT (green line, and labels represent the group mean values of RT). We consider low response time with high accuracy as a true index of progress.

a.



b.

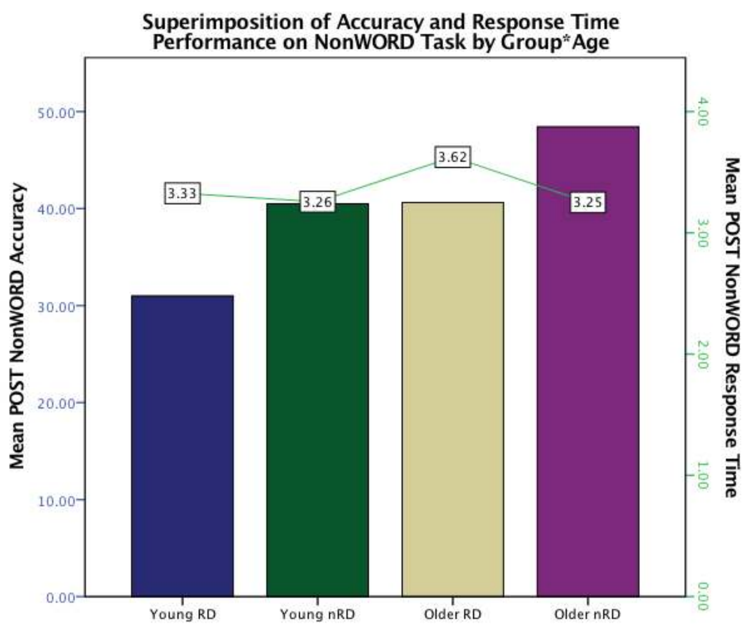


Figure 11. Association of raw POSTTEST means of Response Time and Accuracy scores, as proxy of pre to post training improvement for the WORD (a.) and NonWORD (b.) tasks. Colored boxes

(accuracy), green line (RT).

In association, RT and Accuracy present a new picture of performance, which is not readily observable when considering RT and Accuracy separately. In this illustration, a mark of improvement would be an increase in accuracy coupled with a drop in time, which is the picture we see in the older nRD. Conversely, RDs had a large negative change, when associated with also a drop in response time, this could be interpreted as a sign of precipitation and increase in errors. We must caution however that an increase in response time may also be a sign of increased cautiousness which can be seen in the indices of sensitivity and Decision threshold detailed further.

Sensitivity *(d')*

The groups differed significantly in their sensitivity means (Table 11), and RDs were overall less sensitive to stimuli differences than nRDs at posttest (similarly to baseline). Although non-significant, we observe trends of groups and group*age differences in Figures 12 a. and b. where all groups but Young RDs decreased in sensitivity at posttest.

a. b.

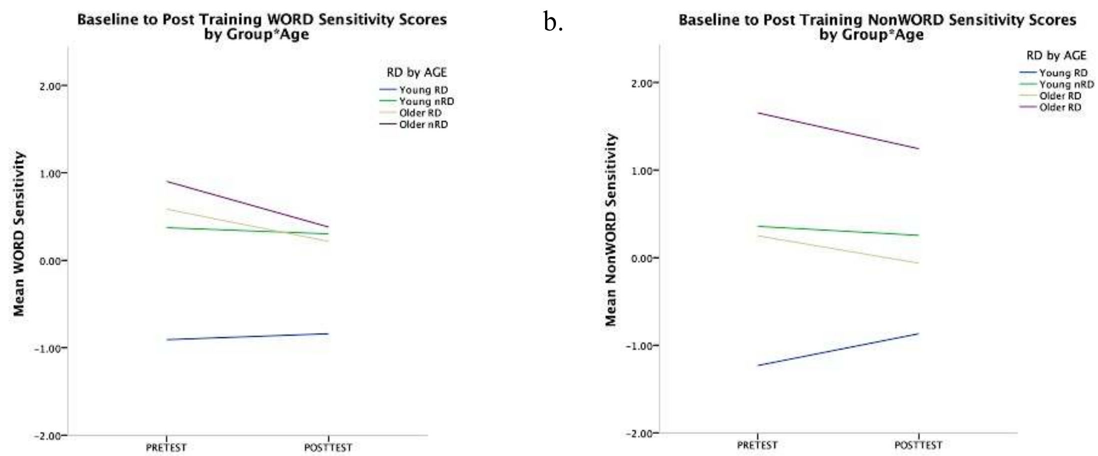


Figure 12. Participants WORD (a.) and NonWORD (b.) sensitivity scores from baseline (Pretest) to after training (Posttest). A higher score is an advantage.

RDs showed a smaller change magnitude (Table 25), but Young RDs were the only group showing an increased response in sensitivity for both tasks. This is interesting and may suggest a tendency for them to be more malleable to learn overtime, and perhaps improve and catch up with the other groups in their ability to discriminate stimuli differences.

Table 11. Means of All Sensitivity (d') for Computer Tasks Scores by Measures, Age, and Group.

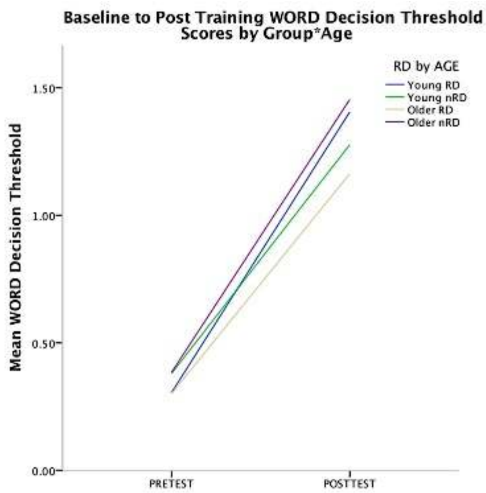
Meas.	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	*SD*	*n*	*p*
d'	Pre WORD	0.316	0.233	19	0.378	0.205	22	0.301	0.158	14	0.358	0.252	13	0.000**
	Post WORD	1.312	0.987	16	1.265	0.971	22	1.163	0.883	14	1.457	0.870	13	0.000**
	Pre NonWORD	0.522	0.542	17	0.503	0.409	21	0.340	0.233	12	0.628	0.433	13	0.000**
	Post NonWORD	0.553	0.291	18	1.088	1.164	22	0.570	0.830	14	0.518	0.383	14	0.000**

Note: *p* is an index of all between groups' significance levels from F statistics from ANOVAs. ** *p*<.001, **p*<.05.

Decision Threshold (*β*)

The groups' means were not significantly different (Table 12). For the WORD task all groups increased in threshold, while only Young nRDs and Older RDs increased on the NonWORD task. The main effects (Figure 13a.) and interactions (Figure 13b.) observed were found non-significant, although there was a marginal Age*Group tendency for the NonWORD task (Group: $F(1,61)=3.399$, $p=.070$).

a.



b.

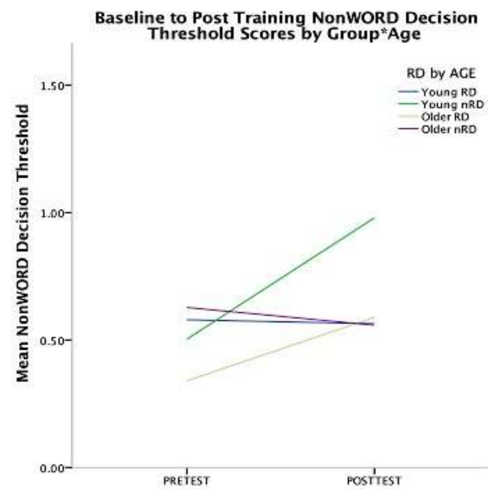


Figure 13. Participants WORD (a.), and NonWORD (b.) Decision Threshold scores from baseline (Pretest) to after training (Posttest). A higher score is an indication of cautiousness.

Table 12. Means of All Decision Threshold Scores for Computer Tasks by Measures, Age, and Group.

Meas.	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	*SD*	*n*	*p*
Beta	PreWORD	-0.908	0.782	20	0.367	0.972	22	0.585	0.889	14	0.902	1.079	13	0.689
	PostWORD	-0.840	0.820	20	0.333	0.853	22	0.215	0.824	14	0.433	1.032	14	0.875
	PreNonWORD	-1.231	1.325	19	0.196	1.507	23	0.178	1.422	14	1.432	1.327	14	0.421
	PostNonWORD	-0.933	1.022	21	0.254	1.312	22	-0.063	1.194	13	1.243	1.159	13	0.087

Note: *p* is an index of all between groups significance levels from F statistics from ANOVAs. ** $p<.001$, *$p<.05$.

Looking at change magnitude means, they were fairly similar on the WORD task for all groups, and RDs showed the least change on the NonWORD task. We cannot, as discussed, judge on whether an increase or decrease may be 'good' or 'bad' when it comes to RD learning as high or low threshold may be dependent on many factors (see our war example). However, coming back to the example of Young RDs who showed low accuracy, low response time, associated with low sensitivity to change and an increasing threshold (or more cautious decisions), we can formulate an image of young RDs having obvious difficulties with LB problems where, after the training, they were found to experience still difficulties getting correct answers, probably because of their hastiness which affected both their sensitivity and seemingly on correct answers were more or cautious, which also reduced their ability to make more correct choices.

Summary of LB Change Scores Analyses

Three questions can be addressed by the data of this section: 1/ Did RD and nRD perform differently at baseline; 2/ How did RDs do at posttest in their language-based tasks after training, and 3/ how much change did they undergo in their language-based problem solving behaviors after that training. At baseline, RD showed lower scores, slower speeds, lower sensitivity and lower threshold across the board on LB tasks. After training, on average as a group (sometimes young was different than older), RDs were still showing lower IQ and WRAT scores, lower accuracies, slower speeds for older RDs and higher for young RDs, less sensitivity, and lower threshold. In terms of change magnitude, RDs had a higher magnitude in IQ (FIQ for young RDs, and VIQ for older RDS); RDs did not show a significant change in academic achievement, they had the lowest change magnitude in accuracy but the highest change in response time (young RDs). RDs also showed the smallest change in sensitivity, and in their threshold. We expected much less change in the language-based areas in the RD group, and this was positively verified. In conclusion, RDs' LB skills were not impacted after a week of training, they continued to show significant struggles to be accurate, discriminate stimuli, and devise strategies to choose the best answers. The post-test RT and accuracy correlations maintained its direction and non-significance after training, which confirms our conclusion (Appendix 3 Table 30).

Table 13. ANOVA results for pre to post scores changes on LB tasks.

	Source	df	F	Sig.	Partial Eta^2	Observed Power
FIQ	Group	1	0.723	0.398	0.010	0.134
	Age	1	0.154	0.696	0.002	0.067
	Group*Age	1	0.465	0.497	0.007	0.103
	Error	70				
VIQ	Group	1	0.150	0.700	0.002	0.067
	Age	1	0.084	0.773	0.001	0.059
	Group*Age	1	0.332	0.567	0.005	0.088
	Error	70				
WRAT Read	Group	1	0.458	0.501	0.007	0.102
	Age	1	3.192	0.078	0.044	0.422
	Group*Age	1	0.141	0.708	0.002	0.066
	Error	70				
WRAT spell	Group	1	1.473	0.229	0.021	0.224
	Age	1	1.478	0.228	0.021	0.224
	Group*Age	1	1.469	0.230	0.021	0.223
	Error	70				
Accu WORD	Group	1	0.076	0.784	0.001	0.058
	Age	1	0.096	0.758	0.001	0.061
	Group*Age	1	0.481	0.490	0.007	0.105
	Error	65				
Accu NonWORD	Group	1	2.201	0.143	0.033	0.309
	Age	1	6.800	0.011**	0.095	0.729
	Group*Age	1	0.290	0.592	0.004	0.083
	Error	65				
RT WORD	Group	1	6.862	0.011**	0.103	0.732
	Age	1	10.221	0.002**	0.146	0.882
	Group*Age	1	3.21	0.078	0.051	0.422
	Error	60				
RT NonWORD	Group	1	6.789	0.012**	0.105	0.726
	Age	1	4.945	0.030**	0.079	0.59
	Group*Age	1	0.503	0.481	0.009	0.107
	Error	58				
d' WORD	Group	1	0.311	0.579	0.005	0.085
	Age	1	2.874	0.095	0.043	0.386
	Group*Age	1	0.001	0.978	0.000	0.050
	Error	64				
d' NonWORD	Group	1	0.886	0.350	0.014	0.153
	Age	1	2.693	0.106	0.041	0.366
	Group*Age	1	0.379	0.540	0.006	0.093
	Error	63				
Beta WORD	Group	1	0.000	0.993	0.000	0.050
	Age	1	0.016	0.899	0.000	0.052
	Group*Age	1	0.639	0.427	0.011	0.123
	Error	57				
Beta NonWORD	Group	1	0.154	0.696	0.003	0.067
	Age	1	0.409	0.525	0.007	0.096
	Group*Age	1	3.399	0.070	0.056	0.442
	Error	57				

Note: Univariate ANOVA computed on ‘change scores’ = post test – pretest. ** significant at the 0.01 level (2-tailed), * significant at the 0.05 level (2-tailed). ‘Sig.’ stands for significance (2-tailed). Partial eta squared: proportion of variance explained by each source main effects.

3.2. RD/nRD Comparison on VS tasks. Hypothesis 2: RDs will show similar VS performance at baseline compared to nRDs and higher or similar performance in VS performances after training.

Baseline VS Performances

PIQ: No statistically significant differences were observed between both groups on Performance IQ, although the RD performed slightly lower (mean Table 14).

Accuracy: Significant differences were observed between both groups on CUBE (F(1,71)=12.215, p=.000), SHAPE (F(1,72)=9.339, p=.000), and 3DIS (F(1,45)=2.687, p=.059) performances. RDs had slightly lower accuracy scores on all three tasks (Table 15).

Response Time: No statistically significant differences were observed between both groups on CUBE, and SHAPE tasks. Significant differences were noted for the 3DIS task (F(1,44)=3.186, p=.034), where (mean Table 16) RDs were slower in CUBE and SHAPE (non-significant), while a bit faster in 3DIS (significant).

***d'*:** Significant differences were observed between both groups on CUBE (F(1,71)=12.267, p=.000), SHAPE (F(1,72)=7.918, p=.000), and 3DIS (F(1,45)=3.582, p=.022) performances. Young RDs were more sensitive in CUBE and SHAPE, while older RDs were more sensitive in SHAPE and 3DIS than nRDs (mean Table 17).

***β*:** Significant differences were observed between both groups on CUBE (F(1,66)=3.131, p=.032), and not in the two other tasks. Young RDs had a lower threshold only on the SHAPE and 3DIS tasks, while older RDs had a higher threshold on the SHAPE and 3DIS tasks (mean Table 18).

Summary. Contrary to our predictions, RDs and nRDs differed in all tasks and measures but PIQ. Also surprising was the tendency of RDs to perform lower on PIQ, and accuracy. RDs were also expected to perform somehow faster, especially 3DIS based on prior research. This was confirmed only for the 3DIS task. We were expecting both groups to differ in sensitivity and decision threshold, which was verified. There were no specific direction expected in that difference as this study was experimental, and we've learned that sensitivity and threshold were here very task and age dependent. Young RDs were more sensitive than older RDs and nRDs on 2/3 of the tasks, while the RD group overall were showing more cautious or conservative decision making on 2/3 of the tasks as well as compared to nRDs.

Pre-to-Post VS Scores Changes Magnitude

After appraising baseline results we were interested in assessing the impact of the VS training in the form of pre to post test change scores. See Table 19 for a summary of all ANOVA results.

PIQ Change Magnitude

The groups did not differ significantly in their PIQ means (Table 14).

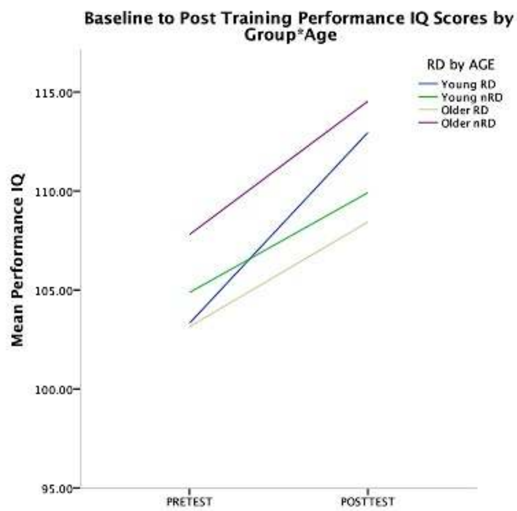


Figure 14. Participants Performance IQ scores from baseline (Pretest) to after training (Posttest). A higher score is an advantage.

Table 14. Means of PIQ by Measures, Age, and Group.

Meas.	Task	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
PIQ	Pre PIQ	103.31	14.43	22	104.87	13.21	23	103.14	12.91	14	107.80	11.01	15	0.735
	Post PIQ	112.95	14.07	22	109.91	16.54	23	108.43	14.91	14	114.53	9.21	15	0.609

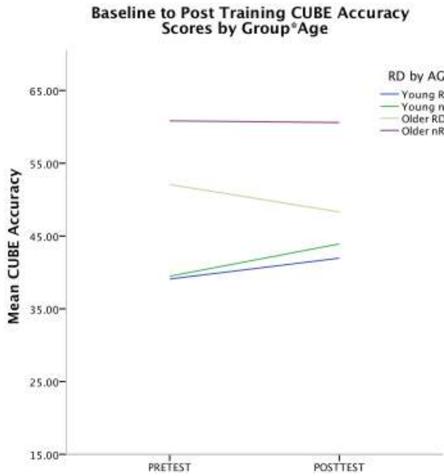
Note: *p* is an index of all between groups significance levels from *F* statistics from ANOVAs. ** $p<.001$, *$p<.05$.

Groups did not significantly differ also in their average PIQ change (Table 19). However young RDs showed the largest overall change (Table 25), although the Age by Group interaction observed is not significant. Young RDs show a pretty high jump in score at Posttest, it leaves to speculate if the specific 3 days VS training may have had a specific influence as they seem to responded uniquely and surpass all but the Older nRDs.

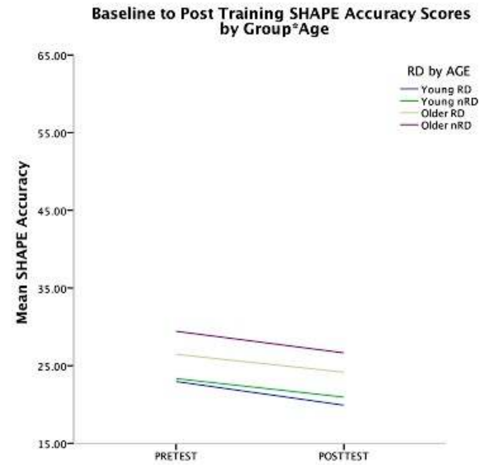
VS Tasks Change Magnitude Accuracy

The groups differed significantly in their means (Table 15), with RDs remaining lower on all three tasks. For the CUBE task, there were multiple significant effects: Group effect ($F(1,68) = 8.895$, $p = .011$); Age effect ($F(1,68) = 18.865$, $p<.001$); marginal Age*Group interaction ($F(1,68)=3.461$, $p=.067$). There was a main effect of age for the SHAPE task ($F(1,67) = 26.495$, $p <.001$). There was a main effect of age for the 3DIS ($F(1,41)=17.732$; $p<.001$). Figures 15a., b., c. show this age general effect with a clear separation between the older and younger participants. Overall, running ANOVAs on the change magnitude for each tasks yielded non-significant results safe for an age effect on the CUBE change magnitude ($F(1,70) = 7.452$, $p = .008$). The RD group showed mostly unsubstantial or even negative change magnitudes, except in the 3DIS task where older RDS seem to display a higher learning jump. These results taken together suggest that the training has not helped increase RDs' accuracy beyond that of nRDs, nor has influenced substantial accuracy change magnitude between baseline and post-training.

a.



b.



c.

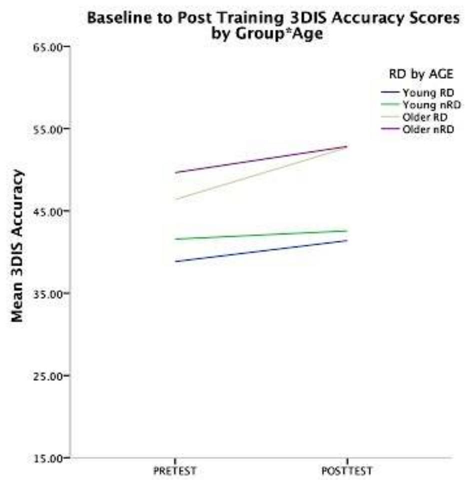


Figure 15. Participants' visuospatial CUBE (a.), SHAPE (b.), and 3DIS (c.) accuracy scores from baseline (pretest) to after training (posttest). Accuracy is computed on the basis of averaged total Hits and Correct Rejections. A higher score is an advantage.

Table 15. Means of All Computer CUBE, SHAPE, and 3DIS Accuracy Tasks Scores by Measures, Age, and Group.

Meas.	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
Accu.	Pre CUBE	39.091	9.981	22	39.478	13.764	23	53.000	14.196	14	60.833	9.013	12	0.000**
	Post CUBE	41.955	10.224	22	43.913	11.200	23	48.308	11.324	13	59.786	8.816	14	0.000**
	Pre SHAPE	22.955	3.124	22	23.318	5.037	22	26.857	4.721	14	29.429	3.155	14	0.000**
	Post SHAPE	19.909	3.308	22	20.727	3.990	22	24.154	4.180	13	26.643	4.940	14	0.000**
	Pre 3DIS	38.214	9.065	14	41.571	9.677	14	46.400	12.267	10	49.571	6.528	7	0.059*
	Post 3DIS	40.786	9.283	14	42.533	10.063	15	52.700	4.692	10	52.833	4.070	6	0.001**

Note: *p* is an index of all between groups significance levels *F* statistics from ANOVAs. ** $p<.001$, *$p<.05$.

VS Tasks Change Magnitude Response Time

The groups differed significantly in their CUBE and SHAPE means (Table 16). There were significant Age effects for CUBE Age effect ($F(1,65)=9.739$, $p=.003$); SHAPE Age effect ($F(1,64)=11.839$, $p=.003$); and 3DIS Age*Group interaction ($F(1,37)=4.009$, $p=.053$). All groups clearly decreased in response times (Figures 16), although Young RDs were faster on CUBE and SHAPE, and older RDs were fastest on the 3DIS task.

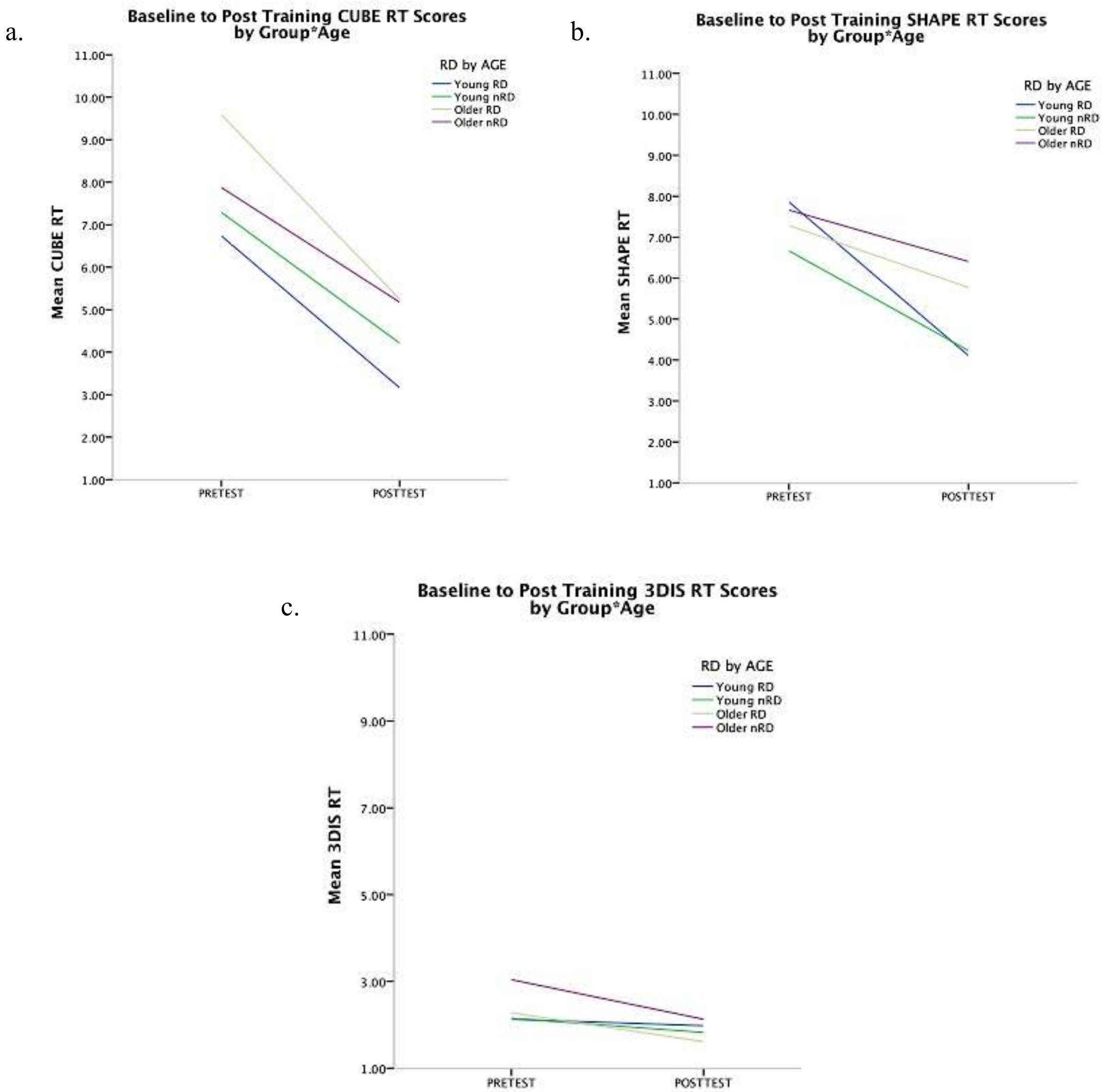


Figure 16. Participants visuospatial CUBE (a.), SHAPE (b.), 3DIS (c.) Response Time scores from baseline (pretest) to after training (posttest). A lower score is an advantage.

Table 16. Means of All Computer CUBE, SHAPE, and 3DIS Response Time Scores by Measures, Age, and Group.

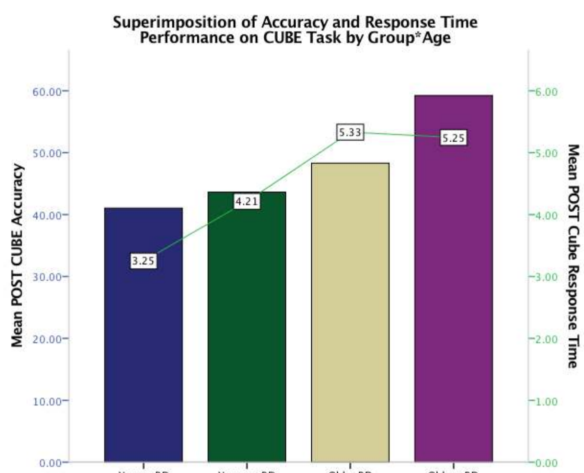
Meas.	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
RT	Pre CUBE	6.737	3.817	20	7.393	4.586	23	9.617	3.403	13	8.277	4.221	12	0.242
	Post CUBE	3.250	2.027	21	4.214	2.430	22	5.331	1.411	13	5.246	1.634	13	0.011**
	Pre SHAPE	7.859	2.681	21	6.478	2.409	21	7.255	2.319	12	7.841	1.860	13	0.242
	Post SHAPE	4.110	2.094	21	4.521	2.322	21	6.164	2.139	13	6.312	2.425	13	0.010**
	Pre 3DIS	2.150	0.948	13	2.148	0.789	14	2.278	0.904	10	3.288	0.849	7	0.034**
	Post 3DIS	1.978	0.444	11	1.823	0.588	15	1.610	0.432	10	2.130	0.408	5	0.216

Note: *p* is an index of all between groups significance levels *F* statistics from ANOVAs. ** p<.001, *p<.05.

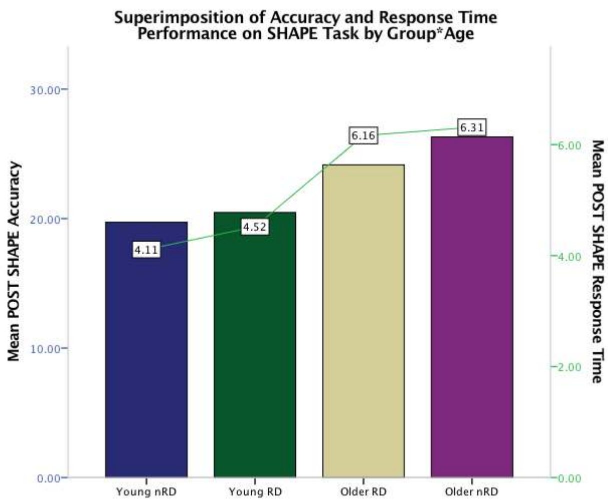
Looking at change magnitude, ANOVA results (Table 19) revealed no significant differences safe for the SHAPE task with an effect of age ($F(1,64) = 7.361$, p =.009). Although generally non-significant, the changes observed from baseline to posttest are indicative of learning, Young RDs seem to have had the widest change on CUBE and SHAPE. That being said, based on our previous accuracy/RT tradeoff discussion, we effected the same graph for VS accuracy and RT (Figure17).

Below are charts in which the Left axis represents Accuracy (colored boxes), and the Right axis represents RT (green line, and labels represent the group mean values of RT). We consider low response time with high accuracy as a true index of progress.

a.



b.



c.

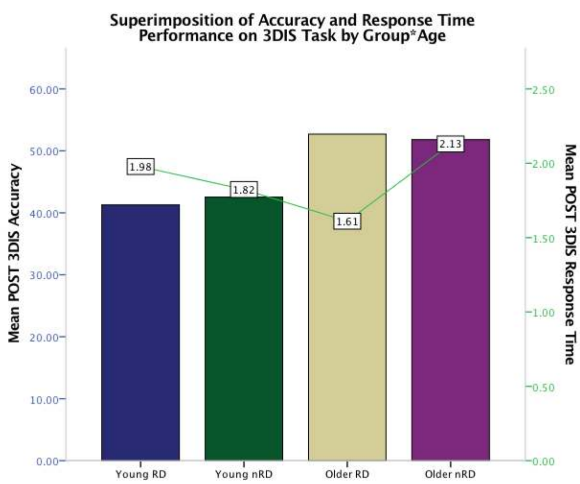
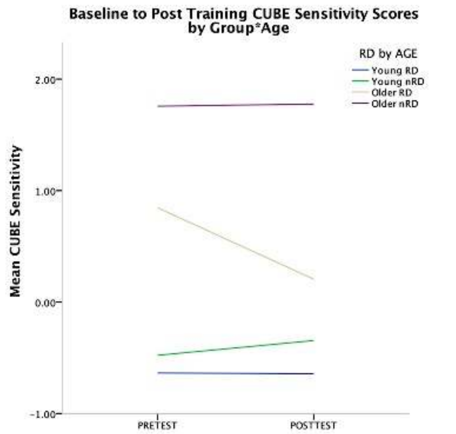


Figure 17. Association of POSTTEST CUBE (a.), SHAPE (b.), and 3DIS (c.) Response Time and Accuracy scores means as proxy of pre to post training VS improvement. Colored boxes (accuracy), green line (RT).

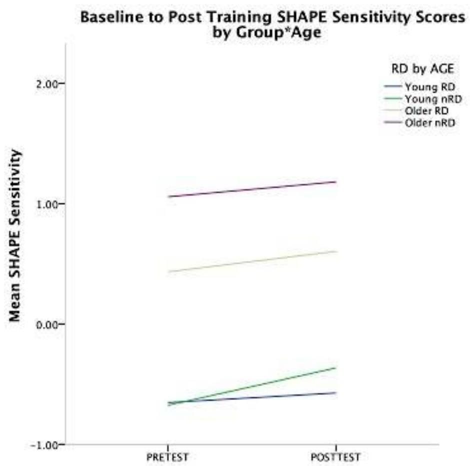
VS Tasks Change Magnitude Sensitivity *(d')*

The groups differed significantly in all their sensitivity means (Table 17). There were significant main effects for CUBE: Group effect (F(1.68)=7.308, p=.009); Age effect (F(1,68)=19.243, p<.001); marginal Age*Group interaction (F(1,68)=3.209, p=.078); for SHAPE Age effect (F(1,68)=26.871, p<.001); and 3DIS Age effect (F(1,43)=11.680, p=.001). Figures 18 do show a general effect of age where the younger groups consistently show less sensitivity at posttest. RDs were less sensitive overall at posttest and both young and older improved slightly in the SHAPE task. Young RDs became less sensitive on CUBE and 3DIS as opposed to their baseline; older RDs became more sensitive in SHAPE and 3DIS as opposed to their baseline and showed a large drop in the CUBE task (Figures 18 a., b., c.).

a.



b.



c.

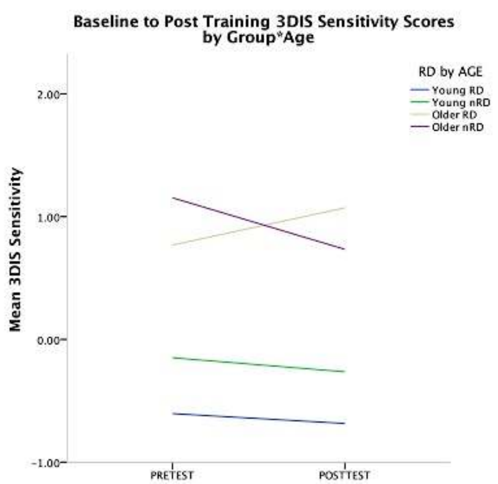


Figure 18. Participants' visuospatial CUBE (a.), SHAPE (b.), and 3DIS (c.) sensitivity scores from baseline (pretest) to after training (posttest). A higher score is an advantage.

Table 17. Means of All Sensitivity (*d'*) for Computer Tasks Scores by Measures, Age, and Group.

Meas.	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
d'	Pre Cube	-0.636	1.084	22	-0.477	1.428	23	0.940	1.579	14	1.757	1.022	12	0.000**
	Post Cube	-0.644	1.329	22	-0.345	1.433	23	0.205	1.434	13	1.675	1.098	14	0.000**
	Pre SHAPE	-0.653	1.027	22	-0.675	1.585	23	0.537	1.313	14	1.057	0.777	13	0.000**
	Post SHAPE	-0.573	0.833	22	-0.365	1.103	23	0.603	1.211	13	1.270	1.396	14	0.000**
	Pre 3DIS	-0.702	1.402	14	-0.149	1.562	14	0.768	1.613	10	1.153	0.770	7	0.022**
	Post 3DIS	-0.817	1.478	14	-0.269	1.393	15	0.864	0.949	11	0.733	1.054	7	0.008**

Note: *p* is an index of all between groups significance levels from F statistics from ANOVAs. ** *p*<.001, **p*<.05.

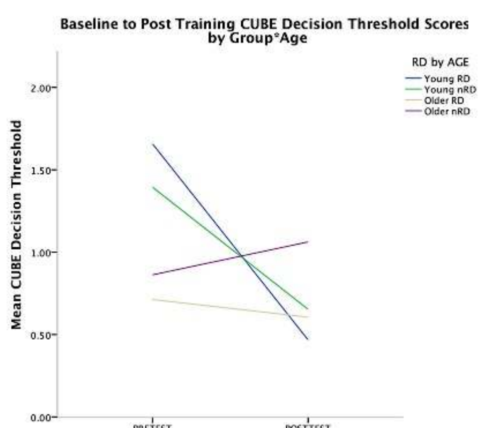
Despite what is apparent in the older groups, all groups' change magnitudes differences were non-significant (Table 19), although the RD group had in average the largest change (in a downward direction).

In conclusion, for all groups, sensitivity did not change substantially from baseline to posttest after training, but once again, RDs did show a larger change, this time in the negative direction. A drop in sensitivity could be a tradeoff here with a faster response time, perhaps a gain of confidence in the RDs group, in their ability to work out these VS problems.

VS Tasks Change Magnitude Decision Threshold *(β)*

The groups did not differ significantly in their posttest means, and RDs dropped in threshold from their baseline and were lower than nRDs at posttest. While the trends observed in Figures 17 a., b., c. were significant only for CUBE with an Age*Group interactions (*F*(1,66)=3.131, *p*=.032), all groups decreased in threshold at posttest on CUBE and SHAPE tasks, and Young RDs were the only group to increase in stringency on the 3DIS task.

a.



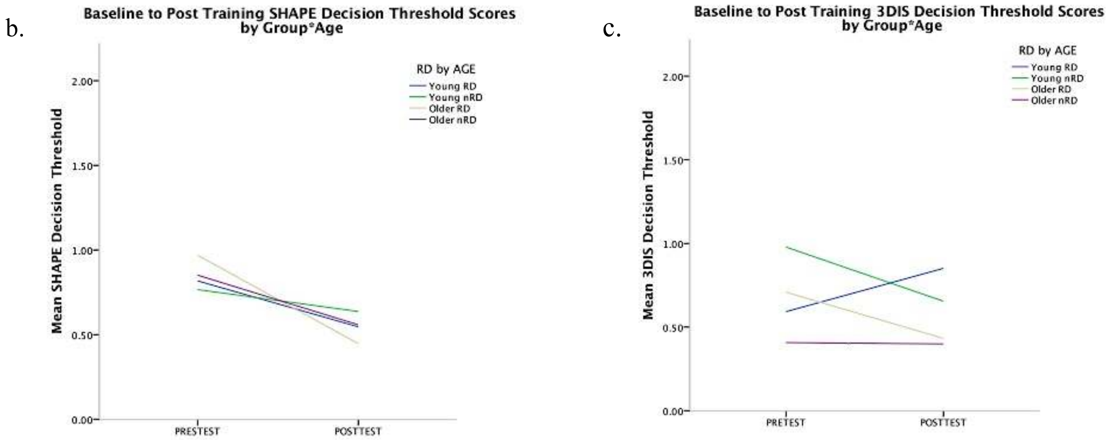


Figure 19. Participants visuospatial CUBE (a.), SHAPE (b.), 3DIS (c.) Decision Threshold scores from baseline (pretest) to after training (posttest). A higher score is an indication of cautiousness.

Table 18. Means of All Decision Threshold Scores for Computer Tasks by Measures, Age, and Group.

Meas.	Tasks	Young RDs *M*	SD	n	Young nRDs *M*	SD	n	Older RDs *M*	SD	n	Older nRDs *M*	SD	n	*p*
Beta	PreCube	1.812	1.306	20	1.395	1.334	20	0.791	0.572	14	0.862	0.633	12	0.032**
	PostCube	0.513	0.570	20	0.651	0.812	21	0.606	0.583	13	1.131	0.876	14	0.095
	PreSHAPE	0.800	0.739	21	0.782	0.637	19	0.943	0.794	14	0.797	0.746	14	0.923
	PostSHAPE	0.554	0.401	20	0.564	0.586	19	0.447	0.294	13	0.558	0.425	11	0.887
	Pre3DIS	0.586	0.415	12	1.001	0.645	13	0.709	1.013	10	0.407	0.240	7	0.236
	Post3DIS	0.818	0.662	10	0.634	0.499	14	0.394	0.266	11	0.399	0.313	7	0.160

Note: *p* is an index of all between groups significance levels from F statistics from ANOVAs. ** $p<.001$, *$p<.05$.

We also observe from the figures some substantial changes slopes, but the change magnitudes were found significantly different only in the CUBE decision threshold with a main effect of age $F(1,63)=11.395$, $p=.001$). The only groups that did not experience a general drop in threshold were young RDs on 3DIS, and older nRDs on CUBE, the rest of the groups exhibit a marked drop in decision threshold on all tasks. The question is, is this a positive or negative finding in the context of learning after VS training? We conclude that the training may have affected the ability of young RDs to be more stringent in their choices on the 3DIS task, but this question needs further study on threshold decision behavior in RDs.

Additional note on change scores

We wanted to take a look at whom exactly were the best among those who improved the most in accuracy (analyses not shown here). We took the percentage of cases within RD and within nRD who achieved a z score >.50 for CUBE, SHAPE, and 3DIS. We discovered that amongst the best 'improvers' there were more RDs. In 3DIS and SHAPE, RDs were more often in the top 28-43% vs. 10-23% in nRDs. In CUBE, Young RDs were more often in the top 28%, with Young nRD vs. 0-20% in older RDs and nRDs. Here there is an age obvious effect again. More research is needed to explore these phenomenon.

Summary of VS Change Scores Analyses

Unlike our expectations, at baseline, as a group RDs performed slightly lower than nRDs on PIQ (p>.05), we were expecting the groups to be quite equal. There were clear age-dependent results: older RDs had the second highest accuracy on computer tasks overall below older nRDs. As we expected, RDs were faster on CUBE and SHAPE. We had less clear expectations for sensitivity and decision threshold, and we found that RDs were overall less sensitive, and had higher thresholds. After receiving the three-days VS training, Young RDs improved more on their PIQ, which we expected to see. Older RDs remained the second highest in computer accuracy scores, but did not surpass their counterparts which we were hoping to see. RDs were still faster on most tasks, sensitivity improved for both young and older RDs, and decision thresholds went down. Compared to their own baseline, Young RDs improved their accuracy, gained speed, improved their sensitivity only on SHAPE, and had a decrease of threshold on CUBE and SHAPE. Older RDs also improved their PIQ, however mostly lost accuracy on computer tasks (which was surprising), were faster overall, mostly improved their sensitivity, and dropped their threshold on all tasks as well. Looking at change, RDs overall had the largest change magnitude in most tasks (10 out of 13 tasks – Table 25). They had the largest positive change in PIQ, all largest in accuracy (dropping on CUBE and SHAPE, increasing on 3DIS), two of the largest changes in RT with the fastest time, two of the largest changes in sensitivity (dropping in CUBE, increasing in SHAPE), and finally two of the largest changes in decision threshold (dropping in both).

Our conclusion here is that, although RDs did not generally dramatically surpass nRDs either at baseline or after training, there was clear self-improvement for RDs, as compared to their own baseline, and their results show them to be the group who’s change magnitudes, or learning was the widest after training. (See Table 25 Appendix 5, for all results summaries.)

Table 19. ANOVA results for pre to post scores changes on VS tasks.

	Source	df	F	Sig.	Partial Eta^2	Observed Power
PIQ	Group	1	0.150	0.700	0.002	0.067
	Age	1	0.084	0.773	0.001	0.059
	Group*Age	1	0.332	0.567	0.005	0.088
	Error	70				
Accu CUBE	Group	1	1.507	0.224	0.022	0.227
	Age	1	7.452	0.008**	0.101	0.767
	Group*Age	1	0.221	0.640	0.003	0.075
	Error	66				
Accu SHAPE	Group	1	0.008	0.929	0.000	0.051
	Age	1	0.026	0.873	0.000	0.053
	Group*Age	1	0.302	0.584	0.005	0.084
	Error	66				
Accu 3DIS	Group	1	0.654	0.424	0.016	0.124
	Age	1	1.052	0.311	0.026	0.170
	Group*Age	1	0.076	0.784	0.002	0.058
	Error	39				
RT CUBE	Group	1	1.159	0.286	0.019	0.185
	Age	1	0.037	0.848	0.001	0.054
	Group*Age	1	0.335	0.565	0.005	0.088
	Error	61				
RT SHAPE	Group	1	1.553	0.218	0.025	0.232
	Age	1	7.361	0.009**	0.109	0.761
	Group*Age	1	0.709	0.403	0.012	0.132
	Error	60				
RT 3DIS	Group	1	0.44	0.511	0.012	0.099
	Age	1	3.114	0.086	0.080	0.404
	Group*Age	1	0.013	0.910	0.000	0.051
	Error	36				
d' CUBE	Group	1	2.646	0.109	0.039	0.361
	Age	1	2.295	0.135	0.034	0.320
	Group*Age	1	1.117	0.294	0.017	0.181
	Error	66				
d' SHAPE	Group	1	0.093	0.761	0.001	0.060
	Age	1	0.026	0.873	0.000	0.053
	Group*Age	1	0.211	0.648	0.003	0.074
	Error	67				
d' 3DIS	Group	1	1.061	0.309	0.026	0.171
	Age	1	0.011	0.916	0.000	0.051
	Group*Age	1	0.879	0.354	0.021	0.150
	Error	40				
Beta CUBE	Group	1	1.588	0.213	0.026	0.236
	Age	1	11.395	0.001**	0.162	0.913
	Group*Age	1	0.056	0.815	0.001	0.056
	Error	59				
Beta SHAPE	Group	1	0.718	0.400	0.013	0.132
	Age	1	0.898	0.347	0.016	0.154
	Group*Age	1	0.039	0.844	0.001	0.054
	Error	55				
Beta 3DIS	Group	1	0.460	0.502	0.013	0.101
	Age	1	0.224	0.639	0.007	0.075
	Group*Age	1	3.373	0.075	0.090	0.430
	Error	34				

Note: Univariate ANOVA computed on 'change scores' = post test – pretest. ** significant "sig" at the 0.01 level (2-tailed), * significant at the 0.05 level (2-tailed). Partial eta squared: variance explained by each source main effects.

3.3. Hypothesis 3: Impact of the Visuospatial Training

Is there a different learning pattern between RD and nRD as they receive VS training?

RDs were expected to perform "better" or improve more than their nRD counter parts generally across training sessions. Analyses were conducted to assess the learning processes of both groups across three time points (3-days of training task scores). Two (Group) by three (3 days of Training) ANOVAs were performed on booklet speed and accuracy indices. Given the nature of the booklets scoring scheme, which involves some measure of subjectivity, interrater reliability Cohen's κ were performed with randomly selected 20 packets scored by two raters. There was 80% agreement among raters.

Although participants are not limited in the time they take for completing the training tasks, each booklet was scored for time to complete each of the 3 types of problem groups, as well as time to complete each booklet in total. Items in the booklets were scored as follows:

a. *Tangrams:* 1 point for correct overall shapes even if the arrangement of the pieces may not be the same as our proposed solution [Total possible points = 6].
b. *Legos:* 1 point for 2 correctly identified images on the same problem, 0.5 if only one image is correctly identified [Total possible points = 6].
c. *WT:* 1 point for every correctly shaded small house [Total possible points = 15].

Time is counted in minutes for each task from the time started to the time it is completed. The following graphs detail the performances of RDs and nRDs by age.

The book means were statistically significant indicating a noticeable score change at each one of the three time points across all the problem types. Mean Book 1 M = 20.71 (SD=4.76), Book 2 M = 22.58 (SD=4.16), Book 3 M = 23.19 (SD=3.55). Note that the minimum score increased overtime (see Table 22), and that the standard deviations decrease overtime, indicating a tightening of the skills among the groups as learning took place. Figure 26 shows the improvement of each groups across the three time points. All groups improved in their problem solving after training, however their final performance ranking remained the same as that of their beginning scores with nRDs doing better.

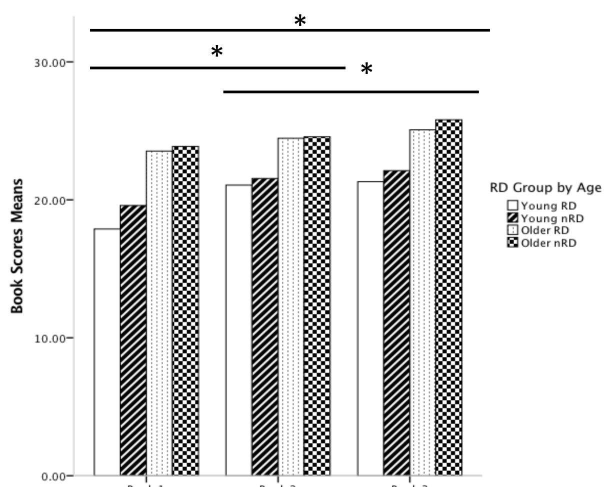


Figure 20. Mean scores for each training booklet by Age by RD. Asterisks indicate statistically significant mean differences (p<.05) across books scores.

A gain score was computed by subtracting the first booklet score from the third to assess if any group ultimately progressed more than another. The young group had the highest gain overall: young RDs 3.43 points up on average, young nRD 2.45; while the older RDs had the smallest gain 1.53, relative to the older nRDs at 1.93, although these change score differences were not significant between groups. Nonetheless, this is the trend we expected given our hypotheses that Young RDs would benefit the most from the VS training having not compensated yet with strategies to circumvent their Language-based challenges, which we argue, may potentially affect their non-Language-based abilities.

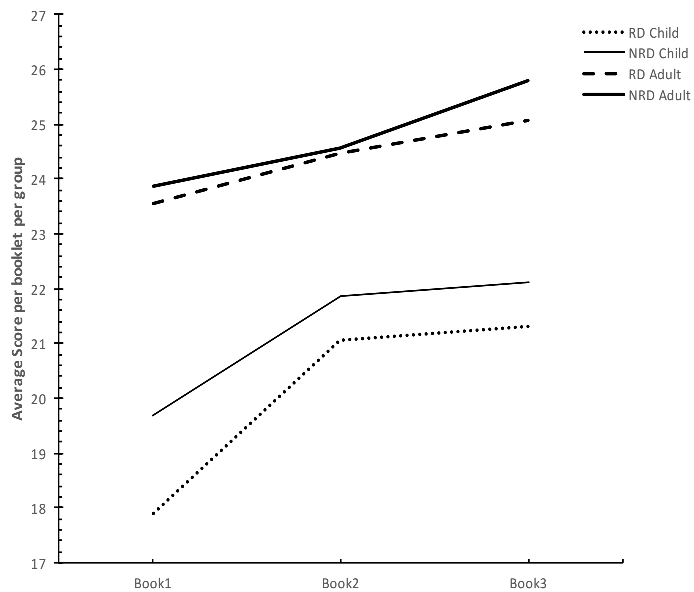


Figure 21. Learning mean book scores across time.

This pattern was the same for each task looked at separately (see Figures 24-26 in Appendix 6).

Table 20. Means of Booklet Total Scores by RD by Age Group.

Time Point	Young RD *M*	SD	n	Young nRD *M*	SD	n	Older RD *M*	SD	n	Older nRD *M*	SD	n	Young RD Gain	Young nRD Gain	Older RD Gain	Older nRD Gain
Book 1	10.9	3.5	22	11.8	3.1	22	13.6	1.5	14	13.6	1.6	15				
Book 2	3.5	1.5	22	3.6	2.1	22	4.5	1.6	14	4.5	1.5	15	3.43	2.52	1.54	1.93
Book 3	12.1	3.1	22	12.9	2.6	22	14.3	0.9	14	13.9	2.5	15				

Note. Gain is calculated by subtracting Book 1 means from Book 3 means.

While all groups improved steadily across trainings, there is some plateauing after session 2, young RDs performed consistently worse than the nRDs regardless of age, and the young RDs performed more poorly than Older RDs. Young RDs had the highest gain on Shapes and Legos, and .01 difference below the young nRDs on the WT (windows test); RD and young nRDs had the highest gain compared to adults on Legos and WT. The RD group had the highest gain only in the Shape task. This is interesting as informal surveying at debriefing indicates that participants in majority found the Shape task to be the hardest of all tasks.

Also indicative of RD behavior with VS problems processing was the average time each group took to complete each book. Note that the sessions were not timed, which can make interpretation somewhat ambiguous.

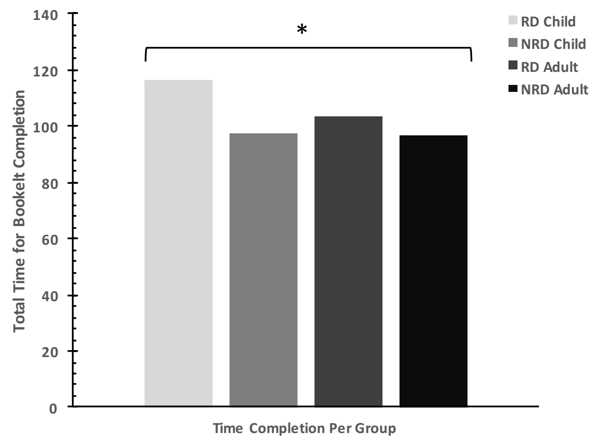


Figure 22. Mean completion time for each training booklet by Age by RD. The asterisk indicates the mean differences significance ($p<.05$) across groups and books scores.

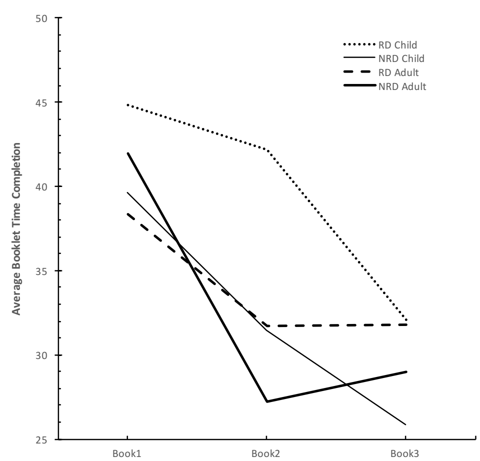


Figure 23. Time completion progression per age per group across the three training days.

Table 21. Means of Booklet Total Completion Time by RD by Age Group.

Time Point	Young RD *M*	SD	n	Young nRD *M*	SD	n	Older RD *M*	SD	n	Older nRD *M*	SD	n	Young RD Gain	Young nRD Gain	Older RD Gain	Older nRD Gain
Book 1	5.4	2.1	16	5.8	3.8	11	4.5	1.5	13	3.7	1.4	14				
Book 2	29.1	13.9	19	20.5	7.3	14	22.5	12.4	14	21.2	6.5	14	-12.74	-13.75	-6.59	-12.93
Book 3	4.6	2.1	18	3.0	1.7	14	3.4	1.6	14	3.6	3.3	15				

Note. Gain is calculated by subtracting Book 1 means from Book 3 means. Negative numbers indicate a decrease in time taken to complete the tasks.

Summary. Both groups improved in problem-solving speed, although the RD group took more time on average to solve their problems at the end of session 3. We hypothesized that RDs' response to training on the books would be better and this was verified particularly for the young group. Looking at the learning curve across time, all groups completed their tasks increasingly faster as they practiced their VS problem-solving strategies. However, RDs took markedly more time on average. Overall young nRDs had the highest time gain which does not confirm the hypothesis that the RDs (especially the young group) would benefit the most from the training. This result does not support the belief that RDs perform faster in general as found in a number of previous studies specifically with mental rotation, puzzles, impossible figures, (Diehl, et al., 2014; Olulade, et al., 2012; von Karolyi, 2001; von Károlyi, et al., 2003; Vakil, et al., 2015; Wang, et al., 2011). This could be due to the addition of manipulatives, or RDs tendency to analyze and cognitively process information in a more energy-consuming pattern. Speculations about this result will be detailed in the discussion.

CHAPTER IV

Discussion

To clarify current empirical knowledge on visuospatial skills in dyslexia, we performed a literature review including over 40 years of research on non-Language-based visuospatial skills in individuals with dyslexia. The search revealed several methodological and empirical issues in the field. Findings partially contradict commonly held beliefs about what may be superior VS skills of individuals with RD. On the contrary, RDs were found to most often underperform or perform similarly to controls on VS tasks (Table 3). However, the available data reflects a narrow use of non-Language-based tasks, a lack of studies on pre-teen ages and below, issues with study designs and types of skills investigated, and a complete lack of assessment of RDs' VS learning abilities (operationalized as marked post-test score increase and posttest response time decrease, evidence of sensitivity to stimuli differences, and response to vocal feedback in the training by showing increase in accuracy and decrease in time to complete each training books). Thus, it is difficult to draw any clear conclusion regarding RDs' VS skills (or VS profile) until more thorough research is done.

As a beginning to investigate the needs in these lacking areas, the present study investigated the developmental trajectory of RDs from the ages of 7 to 26 years old compared to a control group of matched nRD individuals regarding the ability to solve visuospatial problems after a week-long VS training. The first set of analyses in this study compared basic performances at baseline to assess group differences in IQ, academic reading, and spelling achievement, and on a series of computerized tasks that assessed complex visuospatial skills (e.g., spatial rotation, global holistic processing, 3D solids manipulation). Following this first assessment, participants received three days of VS training with books containing three types of tasks enhanced by the use of hand-held manipulatives. A post-training assessment was given on day 5 of the study in which participants repeated all the tasks of the pre-test baseline. Four measures were obtained to compare the two groups on VS performance and learning: accuracy, speed of response, sensitivity to stimuli change, and decision threshold. The following sections summarize the findings.

Before we do so, we must underline that the interpretation of the performance indices of response time, and decision threshold is complex. For example, as we consider the interpretation of response time, we have focused on changes (i.e. progress?) from baseline to post-test. Traditionally, faster RTs are considered to equate 'better' performance. Yet, in the context of some of our more difficult tasks, a slower RT may actually be a sign of progress, as it may reflect a participant's increased cautiousness caused by a deeper reflection on the problem at hand. For example, while it is true that participants may decrease their time because they have developed and can apply more quickly their problem-solving skills, we observed that faster RTs were sometimes associated with more accuracy errors (Figures 11 & 17). Moreover, some learned strategies might actually involve a conscious decision to make choices more slowly to improve accuracy. Thus RT must be interpreted in a broader context, in conjunction with accuracy as we show in correlations Tables 21 and 22 and Figures 11 and 17, to get a true measure of actual pre to post training improvement.

Additionally, there is a non-negligible connection between RT and decision threshold, as becoming more stringent or cautious about one's decision may also slow down the process of response. A decision threshold is a general tendency to respond yes or no, depending on the perception of the participant. That threshold is the cognitive state in which a participant is detecting a stimulus and is willing or not to emit a response (Stanislaw and Todorov, 1999). That index can be very different from participant to participant, yet we wanted to assess if that threshold was unique in RDs as opposed to nRDs. The issue with decision threshold is that a high or low threshold is not so easily interpretable as progress or lack thereof. Indeed, recall that participants had to answer

YES or NO when solving computerized VS and LB tasks. If they responded YES when the correct answer was yes, they scored a HIT, and NO when the correct answer was no, they scored a Correct Rejection; if they answered YES when the correct answer was no, they scored a False Alarm, while a NO response when the correct answer was yes, yielded a MISS.

In their determination of which stimuli deserve affirmative or negative answers, participants become a complex asset. The first issue for researchers interpreting this decision threshold is the fact that this threshold index is very context- or person-dependent. One subject may have a high threshold today and a low threshold tomorrow depending on a number of factors such as tiredness, overall mood, environment and so forth. In that framework, decision threshold may not be such a stable measure as accuracy. The second issue is in interpreting what a low or high threshold really means, which is not straightforward. If someone adopts a higher threshold (meaning they need to be more certain that stimuli match before answering) they might make fewer mistakes, but both hit and correct rejections (or accuracy) rates may go down as well. Is this a sign of progress? If someone adopts a lower threshold (meaning they need less certainty when choosing matching stimuli), they may make more mistakes, but also hits and correct rejections (or accuracy) rates may go up. Is this progress in our VS learning context?

For example, RDs may obtain a fast RT on a task, but that could be coupled with a low accuracy. This is not real progress, but could also be a sign of additional confidence in their responses, for that group, as a result of training. Let's say now that RDs also show low decision threshold in that same task, this could be interpreted as RDs being less stringent or more cautious, which allows them to go faster, but to also make more false alarms and miss. As can be seen in this example, we cannot use the measures obtained as separate proxies for progress, but we have to contemplate their interactions in order to make cautious interpretations of RDs' behavioral outcomes.

IV.1. Discussion of Specific Hypotheses

Three major ideas were explored: (1) RDs will perform similarly to nRDs at baseline on all tasks, although they might show some deficits on LB tasks; (2) RDs will improve more than nRDs at post-test specifically on visuospatial tasks, and there will also be a clear learning difference according to age, with younger participants having a higher and steeper learning/improvement trend; (3) RDs will perform better on booklet training and catch up or surpass nRDs due to their potential affinity for processing non-Language-based information. Note that in what is called the older sample, younger participants were 13 years old adolescents, which is still young, however, research has shown that pubescent teens exhibit a clear change in learning and VS abilities during and after puberty (Gilger & Ho, 1989). We thus expected that their behavior would resemble more that of older RDs, which was confirmed by preliminary exploratory analyses.

1.1. Hypothesis 1: Language-Based Performance Comparisons

How did individuals with RD perform on language-based tasks relative to developmentally normal peers at baseline (pretest)?

Based on prior data, there might be some groups differences on LB performance tasks at baseline (e.g., IQ, academic achievement, rhyming) (Gilger et al, 2016; Paulesu, Démonet, Fazio, McCrory, Chanoine, Brunswick, ... & Frith, 2001; Shankweiler, Crain, Katz, Fowler, Liberman, Brady, ... & Stuebing, 1995; Snowling, 1981, 2001). We hypothesized that the RD group would be similar on FIQ and lower on VIQ: this was partially verified as RDs actually performed lower on both measures. We also expected RDs to perform lower on academic achievement, which was confirmed.

The remainder of our predictions were verified, mainly that RDs were less accurate, and were slower in all LB tasks. We expected a level of difference in sensitivity and decision threshold, although we had no prediction about the direction of these differences safe for perhaps lower sensitivity as it relates to accuracy. This was validated as well, as RDs were less sensitive, and had a lower initial threshold. We did observe an age difference only in sensitivity and decision threshold with younger RDs showing higher scores in both measures.

These results are not surprising as these tasks involve a host of LB skills known to be challenging for populations with RD (i.e. having to spell/blend words and word sounds to discriminate rhyming, writing, or reading). We also learned new information on RD as a group that may show weaknesses in sensitivity to stimuli change and a tendency to show low decision thresholds in responding to LB stimuli.

How did individuals with RD perform on language-based tasks relative to developmentally normal peers at post-test, and did they differ in the magnitude of their scores change from pre to post-test? Were these effects also age-dependent?

Some improvement was expected at posttest, mainly because of practice and statistical regression to the mean effects. We could also see some improvement due to the VS training invoking the growth of such skills as attention, however, this last interpretation is beyond the scope of the present study. That said we also expected that improvement may not bring RDs to surpass their counterparts in LB tasks.

An improvement was indeed observed as compared to baseline performances, especially for the Young RDs (on 80% of the tasks vs. 60% for the older RDs). Breaking it down, RDs improved in FIQ and PIQ and WRAT, however not in accuracy for WORD and NonWORD tasks. RDs also (especially Young RDs) increased in response time, sensitivity and stringency (decision threshold). This may be indicative of RDs' intent to strategize by becoming more stringent (or cautious) in their decisions, and becoming more sensitive while keeping the pace. Unfortunately, this did not translate into greater accuracy. It is possible that longer training may have reversed that tendency, however, as we mentioned before, processing LB information is always a broader challenge for RDs.
Looking at RD improvement as compared to nRDs this time, the picture is quite different, as RDs were more often performing lower, and were slower. They still had high sensitivity and thresholds but often came second to nRDs in that performance.

In the context of change magnitude, we observed an equal change magnitude with both RD and nRD groups showing the largest change in opposite tasks. Also note that, of the tasks in which RDs had the largest change magnitude, Young RDs were more often the group with the largest of both.

The last hypothesis in this context was the expectation of seeing a difference between age groups, and this was confirmed as we detailed throughout this section. Overall, Young RDs had slightly higher sensitivity and threshold scores, increased their baseline results more, and showed larger changes than older nRDs. This suggests a responsivity of younger RD brains to stimuli in a fashion that may warrant more research. Much research has shown the benefit of practice, but none has shown these positive effects happening in a non-language-based training environment. Thus this finding deserves more attention with control study designs that would allow to teasing apart practice effects from changes due to other factors such as the training itself. It would be interesting to investigate if younger RDs would be able to learn and develop better cognitive strategies and capitalizing on what the visuospatial training could enhance cognitively to solve language-based problems (rhyming, vocabulary tasks, reading, and spelling).

1.2. Hypothesis 2: Visuospatial Performance Comparisons

How did individuals with RD perform on visuospatial tasks relative to developmentally normal peers at baseline (pretest)?

Our null hypothesis was that RDs would not differ from nRDs. However, based on prior studies, there might be some RD/nRD group differences. Perhaps RD may show a slight advantage in 3DIS. The results show (in PIQ and Accuracy) that RDs actually did not perform equally or slightly higher, but ranked more often second to a higher nRD group. They were faster in either CUBE (for Young RDs), or SHAPE (for older RDs). We expected RD/nRD differences in sensitivity and decision thresholds and found that RDs had a higher threshold on CUBE (for Young RDs), or SHAPE (for older RDs). Note however that the majority of the data comparing these differences did were not statistically significant for the groups.

Young RDs were generally lower in accuracy, faster, and lower in sensitivity and threshold. These differences were in majority statistically significant.

In conclusion, much like observed in the LB task, at baseline RDs were not equal or surpassing of their peers in means. But they did not look statistically different than nRDs. The lack of statistical significance could reflect a power issue or noise in the data. Therefore, at this stage we cannot reject our null hypotheses that the groups were quite similar in VS skills. However, the slight underperformance found does echo the findings of our literature review, which is not surprising when we reflect back on our argument that LB and VS processing areas overlap largely; it is not superfluous to expect to see also difficulty of processing in certain VS areas or skills.

How did individuals with RD perform on visuospatial tasks relative to developmentally normal peers after training (post-test), did they differ in the magnitude of their scores change from pre to post-test? Were these effects also age-dependent?

We addressed these questions by looking at how much change had occurred pre to post training between RDs and nRDs, and across ages as well. This allowed us to get a developmental picture of the potential effect of VS training, and to make some assessment about if and how younger and older RDs performed differently.

First, as compared to their own training, there was positive improvement for RDs in PIQ, accuracy, and response time, more often in the Young RD group. There was also some slight increase in sensitivity (on SHAPE), and a general decrease in decision threshold across RDs. However, as compared to nRDs, here too, RDs lagged behind in their performance after training. They were more often lower in accuracy and were faster. In terms of sensitivity, Young RDs did decrease, while older RDs increased (highest in 3DIS). Generally also, RDs had lower thresholds, except for Young RDs showing the highest threshold in 3DIS.

Taken together, so far the results reflect a similar picture as what we saw in the LB tasks, with a low accuracy and yet a faster response time. This speed/accuracy tradeoff has not typically been taken into account in prior research, yet it gives a valuable sense of true improvement. Figure 17 sheds some additional light on the results when overlapping both RT and accuracy and showing that RDs did not show the best progress (high accuracy with low response time) overall. The best improvement observed was only for older RDs in the SHAPE and 3DIS tasks, but Young RDs were consistently in a less favorable position in these measures. All measures associated, we may see here a picture of RDs being somewhat hasty (low RT), and getting less accurate, even though they managed to be less cautious overtime (lowering of decision threshold which could increase the likelihood find more right answers), with a tendency to discriminate stimuli better (increase in sensitivity). Once again, this could be a trend toward improvement for RDs, which may have been seen with a larger sample, more power, and perhaps a longer training treatment. Note here too that none of the group comparisons were statistically significant. Thus the differences observed are marginal and may not suggest such a large difference between RDs and nRDs.

Pertaining to change magnitude (learning effect), which we expected to be greater for RDs, we see a net wider change magnitude for RDs (80% of the categories tested). Notice that some of the changes have a negative sign, which means for example progress in RT (change = post-pre, and we want a smaller post score), but is not positive for accuracy where a higher posttest score is preferable. We also see a larger negative change in sensitivity and stringency for RDs, which means that they had larger substantial drops in both stimuli discrimination and stringency after training. Of the tasks where they had the largest change magnitude, Younger and Older RDs were shared the higher rank equally. The anova change results were not significant for groups.

Finally, we did observe some age differences as expected, but this seemed to be more attenuated in performance and change magnitude between Young and Older RDs. The age differences were not as pronounced here, expect for the comparison of improvement as compared to RDs' own baseline. However, all differences observed were significant.

To conclude this section, we were assessing the effect of a three-day long VS training on changes in VS performances between baseline and posttest. RDs did not surpass their counterparts after receiving the training, they did, however, increase in general performances as compared to their own baseline, and showed a larger change magnitude than the nRD group, which may be indicative of a specialized or unique response to specific VS problem-solving situations. Even though the results were not statistically significant, we caution to explore further the trends observed to assess if power was the reason or an actual non-differences in RD VS processing compared to nRD populations.

Overall, the LB and VS findings were often mediated by age differences, and young RDs often came out as the group that showed large change magnitudes.

As claimed by Gabrieli and Norton (2012) and Kujala et al. (2001), VS training could potentially impact non-language-based and language-based abilities alike. In our case, we are not able to partial out practice effect. Besides, any improvement or larger change observed was task-dependent (which reinforces that researchers should extend our proposed design to other types of VS skills to comprehensively assess the merits of VS training for RD populations). Thus our takeaway here is that the question of the impact of VS training on LB and VS cognitive skills may be more complex than initially thought. Additionally, more in-depth work with RD samples is necessary to understand the developmental age-related trends differences observed. This may provide important insight regarding how RDs develop and could benefit early from VS training (Newcombe & Shipley, 2014).

More research is necessary to confirm the trends we observed with larger samples, more conditions, and more control conditions. Important questions could cover if the changes observed constitute an improvement, and could the effect last over time, and transfer to other academic skills? Which part of the training may have been most helpful? RDs' performances improved (sometimes very marginally sometimes substantially) and had thresholds changes across language-based and VS scores. Does this suggest that VS-types of trainings can alter neural cognitive processes beyond VS processing centers? What is the connection between Language-based and non-Language-based pathways? How robust would this improvement be (Gabrieli & Norton, 2012; Horowitz-Kraus & Holland, 2015; Kujala et al., 2001)?

1.3. Hypothesis 3: Impact of the Visuospatial Training

Is there a difference in learning patterns for RDs and nRDs as they undergo 3-days VS training? No past research used manipulatives as in the present design; thus, it is impossible to compare data. However, Cass et al. (2003) studied students with various learning disabilities and found that manipulatives enhance learning and promote retention and transfer of problem-solving skills across time and domains of learning. The effect of manipulatives in RD VS training requires further exploration in future research. This addition could slow down the already struggling RD group, but also improve their performance. RDs were expected to perform better and faster on the three booklets training tasks. Past researchers suggested that RDs perform better, similarly, or mostly worse than nRDs on similar tasks as those used in the booklets, which made us expect task-dependent results (See Tables 2 & 3). Results revealed that both RDs and nRDs improved in accuracy between book 1 and 3. Participants showed a tightening of their performance in the form of a decrease in overall standard deviations of each days' results over the span of the 3-day long training. The progression of accuracy was age and group dependent. Young RDs remained lower than young nRDs, and the same relation remained true in the older RD/nRD groups. Despite performing lower overall, however, Young RDs improved the most. These results were the same for each task across all groups. Like the results for the pre-post-test, the RD group performed on average lower than the nRD group and took more time to complete tasks, especially the young group. However, Young RDs took significantly less time to complete their tasks, and the young nRDs had the best time gain. To conclude, RDs and nRDs performed significantly different in the training. Both groups improved, but the RD group had the most accuracy improvement benefit from the training despite still lagging on performance over time.

Conclusion of General Hypotheses

After receiving a 3-Day long VS training, RD participants showed a general improvement in their scores (sometimes marginal, sometimes substantial), and larger change (or learning) magnitude slopes. They did not, however, surpass their counterparts in raw scores, but their underperformance was statistically significant only for age.

We can conclude that the training may have been successful in slightly shifting RDs' initial performances, but to a lesser extent than we expected, while uncovering a clear positive responsivity to VS training for younger groups which deserves attention. We do have questions as to how effective the training has been in its current form. RDs may benefit from more empirical work on their VS learning potential through tailored training.

We also encountered some unexpected results such as a wide lack of statistical significance for group differences. We attribute this issue generally to lack of power and some design features that could be improved. Additionally, the interpretation of results (i.e. prior discussion on RT vs. Accuracy) was sometimes complex. For example, results were to be interpreted differently based on their direction, such as faster RT cannot actually mean improvement if it is paired with low accuracy and low decision thresholds, or, lower RT is potentially positive for a participant's skills, while lower accuracy isn't.

Also, based on the generally better results in Young RDs, we wonder if the typical remedial Language-based training of children with dyslexia, and later interventions that help them compensate, does not significantly change their brain structures at the detriment of existing VS abilities. The age by group differences found in this study may suggest that young RDs perhaps have greater potential to develop higher VS skills. The smaller differences observed in the older RD group may indicate that their compensation or life training could have altered these initial abilities. This study is a first step in investigating this hypothesis. More research is necessary to expand these findings.

IV.2. Limitations

This was the first study of its kind, and the challenges encountered allowed us to clear up a path for future researchers to explore our question better informed on the complexities of studying VS skills in controlled environments. There were 4 major issues:

Data Collection & Sample Quality

Building a large RD sample was a challenging task in our region, and the small sample reduced our statistical power. While we expanded our ascertainment areas to more distant communities, budget and time constraints required that we stop sampling at 90 original subjects. We also uncovered a widespread lack of professional diagnostic assessments in many participants, especially those of college-age, who came to us with suspicions about their challenges but no recourse to afford expert assessments. These cases could generally not be added to our sample. We had to remove a substantial number of potential participants from the study for these and other reasons, which further limited the final sample. Consequently, while the trends we observed are promising, we cannot, at this point, be certain of their robustness and validity until the study can be replicated with a larger and more diverse sample. This issue is particularly salient when we examined the effects of age. While age seemed to be an important factor in the data, the small cell sizes precluded the drawing of firm conclusions.

Also, despite strong efforts to access minority groups, the final sample was mainly of Caucasian descent and from high-income families. Future researchers should strive to establish relationships with local school authorities to access larger and more diverse samples in the community. Our efforts have opened doors in that direction and future work seems to be possible with our schools. This may create better cohesion for the network initiated through this period, and help develop better infrastructures for children and adults with dyslexia in the San Joaquin Valley. Pioneering work began with the Consortium for Research on Atypical Development and Learning (CRADL) and the Help for My Child (H4MC) initiative at the University of California Merced. The hope is to continue to develop and strengthen these establishments as resources for RD populations and academics in the region.

Design

After assessing what information we were able to gather out of our current design, we concluded that a control group would have been a substantial help in parsing out practice effects and regressions to the mean, and clarify if the VS training had an impact.

Another issue is the training paradigm. Initially, we proposed 8 days of training and a much larger battery of tests. After piloting the study, and because of the ascertainment constraints mentioned above, we had to limit the design to fewer tests and a shorter training period. We believe that this may have impacted our results by limiting our ability to use more tests of dyslexic symptoms, unique spatial skills, and more. Additionally, a longer training of a different design may have been a better test of our hypotheses. In fact, our original design considered these modifications, as well as the inclusion of three testings rather than just pre and post data points. Having multiple testing data points, along with additional training sessions will provide future work with a better evaluation of learning over time.

Another design question that came to mind is the issue with the type of tasks used in prior studies. Despite the innovative approach of our study, a wider battery of tests could have included tasks such as virtual reality, drawing, closure tasks and so forth. These tasks have been used scarcely, and when used they were not placed in a pre-post/training-learning context. Thus our study could have been a confirmation of some of the results reported, and an extension of tasks not tested before. Though we have used classical and more modern tasks, we believe that we could have done more and thereby strengthen our findings.

Testing Conditions & Sample Quality

Finally, while on diverse testing locations, we ensured a standard testing setting (recurrent same researchers, quiet room, table chairs, identical materials, and as much as possible atmosphere and level of noise). Testing in different locations ensured diversity and better representativeness in the sample but may have introduced unwanted variance.

IV.3. Conclusion and Future Research Directions

We first ascertained the state of the empirical data on visuospatial skills in populations with dyslexia. It is important that researchers first understand where the field stands so that future work can be appropriately guided. Our literature investigation revealed that, in the case of VS abilities in people with RD, many gaps exist. Several lines of research may improve our understanding of the RD population and neurology in general and will guide as to how best support this unique group of individuals. First, researchers must jointly consider performance, learning capacity, and growth or development over time. Because of the difference between behavioral outcomes and cognitive processes (see below the "dissociated function" issue highlighted by Gilger et al., 2013), the approach proposed in this study should provide a much more holistic perspective on the uniqueness of RD cognitive profiles. Secondly, children with RD are a vulnerable and malleable population, and while they are typically the focus of research on the disability part of the RD equation, they have been relatively minimized in studies looking at VS and other skills. As VS skills are a part of the cognitive profile of children with RD, a recommended goal is to understand the cognitive and behavioral states of these children beyond their reading struggles. Thus, a broad approach to the profile of brain-behavior relationships and expressions is needed so that the challenges faced by these children throughout their lives might be ameliorated better than they are today.

Learning vs. Performance

This dissertation demonstrated interesting trends related to providing VS training to RD populations. First, baseline results confirmed what the literature review highlighted: the lack of RD superiority in several VS skills areas. However, this study did not test some of the raw performances of the RD group on other VS skills such as drawing, virtual navigation, recall and so on, which could have been seen in a new light based on the addition of the training, and perhaps the use of other tools rather than paper-pencil or 2D screen images.

Secondly, post-test results combined with the booklet results highlighted RDs somehow showing higher learning increase after training than nRDs; given the marginal significance, this requires replication. Future studies should focus on replicating our design with a larger and more diverse sample. There should also be a testing of learning effect by additional time (longer training), means, and measures. A hierarchical growth model tested on a larger sample may result in different perspectives on the RD learning path and highlight age and developmental trends. Future research should also focus on using a similar longitudinal model with different tasks based on the lack of certain VS skills (see Table 3). Given the lack of information in these areas, researchers should investigate these skills in RD populations to clarify areas of strength and weakness compared to nRDs.

Age

Discovering the general effect of age in the results confirmed the difference in cognitive processes between RD uncompensated children and RD compensated (remediated) older teens and adults. It is not possible to make clear conjectures regarding predispositions of RD brains to deal with VS information that may become hindered by concentrated language-based reading/spelling training. However, the fact that children differed so clearly in their tasks outcomes suggests the existence of a potential sensitive period of in VS and LB skills development. Innovative research is necessary to confirm these trends (Newcombe & Shipley, 2014). The literature review included very few studies of younger RD populations - i.e. under 6 (Uttal et al., 2013). This dissertation is a call to action for researchers to better understand in what capacity older and younger RDs differ, and what happens at the cognitive and behavioral level as younger RDs develop.

Modalities

Past researchers used paper-pencil testing to investigate dynamic/complex and static/simple skills, but few incorporated virtual/3D RD skills, spatial navigation, or art skills (See Table 3). This dissertation conceptualized other means to study RD skills by using computers and virtual reality. A first step was to create a 3D game, which researchers are currently piloting in the CRADL lab. The results from this study yielded other potential directions to explore to improve modality in the domain of VS in RD.

Behavior vs. Process

Some of the results reflect Gilger et al. (2013) regarding the clear differentiation between behavioral outcomes and cognitive processes. This is a dissociated functions hypothesis. Gilger et al. (2013) showed that it was not enough to stop at the performance; cognitive processes involved in VS tasks between RDs and nRDs were clearly different. The use of fMRI technology made it possible to understand that, despite similar results, RDs exhibit a very different cognitive profile than nRDs. This is important in terms of the educational methods that support populations with RD. In this study, RDs showed similar results as nRDs; the findings do not confirm unique cognitive processing profiles when learning and working on VS problems. That being said, the large improvement difference may be a sign of this behavior cognition difference. Newcombe and Shipley (2014) described the unique distinctive neural activation in spatial environments and tested their hypothesis in the virtual domain. The perspective of a longitudinal design and pre-/post-training brain imaging could test this dissociated functions hypothesis. The goal of these suggestions is to motivate researchers to challenge the present findings and develop creative solutions for the complex questions regarding the cognitive profiles of people of all ages with RD.

APPENDIX 1

Questionnaire

Participant Name: ______________________Participant ID:__________ Researcher:_______________________

Questionnaire

Gender: M □ F □

Date of Birth: ____________ Age:_________________Ethnicity:_______________Lefty/Righty?_____________

Education level: ___________________________Major:__N/A___________________ GPA:__________

What languages are spoken in the home? ____

Which of the above languages was introduced to your child *first*?
____

Which of the above languages is used *most*? ____

Have your child ever been diagnosed with a learning disability? Y □ N □

If so, what type? ____

Do you suspect/know that your child has a learning disability? Y □ N □
If so, what type? ____

Do you suspect/know that your child has any psychiatric disability/diagnoses? Y □ N □

If so, what type? ____

Has your child experienced any brain trauma or related accident where you may have lost consciousness? Y □ N □
Does your child play computer/video games? Y □ N □

If so, what type? ____

How much time does your child spend on these games each week? __________

Education

Please answer the following questions. You are free to leave items blank. Please write the letter answer on the line to the right.

1. Did your child experience difficulty in learning to read? ______
   a. No
   b. Yes
   c. Don't know
   Details: ____

Participant Name: ____________________Participant ID:_________ Researcher:_____________________

2. Did your child ever require tutoring or remedial reading class during your education? ______
   a. No
   b. Little (extra help by a teacher)
   c. Moderate (1 academic year or 1 summer)
   d. Great Deal (2 or more academic years or summers)
   e. Don't know

   Details:
   ____
   ____
   ____

3. Did your child ever repeat any grades due to academic failure? ______
   a. No
   b. 1 grade repeated, did not drop out of school
   c. 2 or more grades repeated, did not drop out of school
   d. 1 or more grade repeated, dropped out of school
   e. Don't know

      Details: ____

4. How would you compare your child's spelling to others of the same age and education? ______
   a. Above average
   b. Average
   c. Below average; not very good
   d. Poor; terrible

      Details: ____

5. Does your child have difficulty remembering peoples' names or names of places? ______
   a. No
   b. Little
   c. Moderate
   d. Great deal

      Details: ____

6. Does your child have difficulty remembering days of the week or months of the year? ______
   a. No
   b. Little
   c. Moderate
   d. Great deal

      Details: ____

7. Does your child ever reverse the order of letters or numbers when you read or write? ______
   a. No
   b. I did when younger, but not now.
   c. Once in a while
   d. Regularly, it's a problem for me

      Details:____

Participant Name: ______________________Participant ID:__________ Researcher:______________________

8. What is your child's attitude toward reading? _______
    a. Do as little as possible –don't like to read
    b. Indifferent – not my favorite pastime, buts "its ok" – I don't dislike reading.
    c. Enjoys it – pleasurable
    d. Very positive, enthusiastic – I really enjoy it.
    Details: ____

9. How many books does your child read at home per week? _______
    a. None
    b. 1-5 per week
    c. 6-10 per week
    d. more than 10
    Details: ____

10. Have your ever read to your child? _______
    a. Never
    b. Rarely
    c. Yes or sometimes
    d. Regularly, I love to.
    Details: ____

11. How would you describe your child's school performance (primary school to highschool)? (check the category that applies).

	Reading	Math	Science	Art	Writing/Spelling-
As-Bs					
Bs-Cs					
Cs-Ds					
Ds-Fs					

12. Are there any additional comments you would like to make about your child educationally? Did your child get any remediation of any sort, hard time learning basics, reading, spelling, comprehending …?

____

____

Activities

Please answer the following questions regarding your child's skills and recreational activities. You are free to leave items blank.

13. Briefly list the types of recreation (sports, games, TV, hobbies, etc.) that your child enjoys:
    ____

14.Complete the table below by checking the appropriate boxes. Check one box per ability. The Research Assistant can help explain what is meant by some of these abilities if you have any questions.

Participant Name: ______________________Participant ID:__________ Researcher:_______________________

Area, Skill or Task	**Ability Assessment Relative to Peers of your child**				
	Poor	Below Average	Average	Above Average	Exceptional
Art (Painting)					
Art (Sketching)					
Art (Sculpting)					
Art (Other)					
Music (Instrument)					
Music (Singing)					
Music (Other)					
One or More Sports					
Fine Motor Skills					
Gross Motor Skills					
Visual Matching					
Design or Construction					
Geometry					
Other Math Skill					
Visual Copying					
Visual Maze or Puzzle Solving					
Reading Nonverbal Communication					
Reading People or Their Emotional States					
Other					

Parent History

Please answer the following questions to the best of your recollection ***about*** your child's ***BIOLOGICAL parents***. You are free to leave items blank with NA. Please write the letter answer on the line to the right, if applicable.

1. Highest degree earned: Mother____________________________Father_______________________________

2. Were they ever held back to repeat a grade?

Participant Name: ____________________Participant ID:_________ Researcher:_____________________

MOTHER ______
a. Yes
b. No
If yes, what grade(s)? ______________and reason?______________________

FATHER ______
a. Yes
b. No
If yes, what grade(s)? ______________and reason?______________________

3. Were they in any special class(es) or received special services?

MOTHER ______
a. Yes
b. No
If yes, what grade(s)______ or age(s)?_____and what type of class(es)?____

FATHER ______
c. Yes
d. No
If yes, what grade(s)______ or age(s)?_____and what type of class(es)?____

4. Were they ever diagnosed as having a learning problem or disorder?

MOTHER ______
a. Yes
b. No
If yes, do you recall how it was described or what it was called?
____

FATHER ______
c. Yes
d. No
If yes, do you recall how it was described or what it was called?
____

5. Current job title: MOTHER_______________P/F_____FATHER____________________ P/F _____
(Full Time = F, Part time =P)
6. Approximate yearly gross salary: MOTHER____________________FATHER___________________

Family History
Please answer the following questions regarding your child and his/her family history. Place an "X" in the column under a family member if that family member ever showed that trait of condition. If there are

Participant Name: ______________________Participant ID:__________ Researcher:_______________________

more than one brother and sister indicate it in the same box. Feel free to make written comments, but this is not necessary. You are free to leave items blank.

Condition, State or Trait	**Family Member**				
	Your ChILD	**Bio Mother**	**Bio Father**	**Bio Brother**	**Bio Sister**
Allergies					
Autoimmune Disorder					
Brain Injury					
Neurological Disorder					
Seizures					
Learning Disability					
Speech or Language Disorder					
Attention Deficit Disorder					
Psychiatric Diagnosis					
Mental Retardation					
Asperger Syndrome					
Autism					
Motor Disorder					
Developmental Disorders (Other)					
Specific Genetic or Chromosomal Condition					
Currently On Medications for Any of the Above Named Conditions?					
"Nonverbal" Talents or Special Skills (e.g., insert art, music, athletics, puzzles, math, etc.)?					
"Verbal" Talents or Special Skills (e.g., insert good speaker, large vocabulary, good writer or speller, good memory for words, etc.)?					
Any Comments on These or More Extended Family Members?					

APPENDIX 2

Participant Name: ______________________Participant ID:__________ Researcher:_______________________

Think back to the last three years and indicate on a scale from 0 to 6 (0 being never, or almost never and 6 being daily) how often your child has done each of the following. Write the number (0, 1, 2, 3, 4, 5, or 6) that fits with how often on the line to the right of the item.

|Never ____ | ____ | ____ |Sometimes | ____ | ____ |Daily
0 1 2 3 4 5 6

1. Played with toy cars, planes, etc. ______
2. Worked on jig-saw puzzles ______
3. Took apart and re-assembled "real-things" (e.g., old clocks) ______
4. Built models from kits ______
5. Played with a train or autoracing set. ______
6. Made things by cutting and folding paper ______
7. Built "forts" to play in (e.g., tree-houses, and other structures) ______
8. Worked on nonverbal paper and pencil puzzles (e.g., mazes, connect dots, etc.) ______
9. Sewed or made things from patterns ______
10. Played chess or checkers ______
11. Drafted or designed things to scale. ______
12. Did craftwork using heavy materials (e.g., sculpting, carving, pottery) ______
13. Helped with house repairs ______
14. Did craftwork using light materials (e.g., needlepoint, macramé, weaving). ______
15. Made things with paper-maché, clay, etc. ______
16. Drew or painted pictures (freehand, using own creativity) ______
17. Played pool or billiards ______
18. Did carpentry, made or repaired furniture ______
19. Used a map, compass, atlas, or globe (e.g., to plan routes) ______
20. Made lists (e.g., shopping lists, guest lists, "to-do" lists). ______
21. Played games or sports involving aiming at targets (e.g., darts) ______
22. Worked on math puzzles or problems. ______
23. Took photographs ______
24. Sketched house plans, other designs (e.g., auto or clothes designs). ______
25. Arranged furniture, decorated or redecorated rooms. ______

APPENDIX 3

Table 22. Correlation matrix between sensitivity and decision threshold.

Measure	Task	Sig.	Decision Threshold									
			Pre CUBE	Post CUBE	Pre SHAPE	Post SHAPE	Pre 3DIS	Post 3DIS	Pre WORD	Post WORD	Pre Non WORD	Post Non WORD
Sensitivity	Pre CUBE	*r*	**-.543****	-0.103	0.082	-0.155	0.014	-0.216	0.009	-0.014	-0.019	-0.028
		Sig.	0.000	0.394	0.496	0.208	0.927	0.154	0.941	0.908	0.882	0.818
		n	69	71	71	68	45	45	70	69	66	70
	Post CUBE	r	**-.371****	-0.036	0.112	-0.061	0.045	-0.291	0.004	0.083	-0.011	0.044
		Sig.	0.002	0.767	0.352	0.622	0.767	0.053	0.972	0.496	0.929	0.718
		n	69	71	71	68	45	45	70	69	66	70
	Pre SHAPE	r	**-.363****	-0.045	0.068	-0.080	-0.092	-0.100	-0.137	0.014	-0.170	-0.070
		Sig.	0.002	0.709	0.572	0.514	0.548	0.514	0.257	0.909	0.172	0.564
		n	69	71	71	68	45	45	70	69	66	70
	Post SHAPE	r	-0.207	-0.001	0.040	-0.009	-0.015	-0.118	-0.084	0.020	-0.115	-0.064
		Sig.	0.087	0.993	0.742	0.942	0.923	0.439	0.489	0.870	0.358	0.600
		n	69	71	71	68	45	45	70	69	66	70
	Pre 3DIS	r	-0.185	**.309***	0.043	0.003	-0.268	**-.523****	0.142	-0.108	-0.010	-0.018
		Sig.	0.228	0.039	0.784	0.983	0.076	0.000	0.359	0.486	0.947	0.908
		n	44	45	44	44	45	43	44	44	43	44
	Post 3DIS	r	**-.335***	-0.058	0.060	0.044	-0.169	**-.502****	-0.186	-0.154	-0.105	0.074
		Sig.	0.024	0.702	0.693	0.776	0.273	0.000	0.221	0.313	0.503	0.628
		n	45	46	45	45	44	45	45	45	43	45
	Pre WORD	r	**-.291***	0.019	0.168	0.058	-0.025	-0.301	0.106	-0.107	0.062	-0.021
		Sig.	0.016	0.879	0.172	0.644	0.874	0.050	0.385	0.388	0.622	0.868
		n	68	68	68	66	43	43	70	67	66	68
	Post WORD	r	-0.137	0.127	0.139	0.048	-0.298	-0.231	0.014	**-.338****	-0.080	-0.173
		Sig.	0.270	0.298	0.255	0.702	0.053	0.132	0.910	0.005	0.527	0.152
		n	67	69	69	66	43	44	69	69	65	70
	Pre Non WORD	r	-0.213	0.013	0.167	0.117	0.043	-0.213	-0.015	-0.006	**-.274***	0.137
		Sig.	0.081	0.917	0.174	0.348	0.783	0.171	0.901	0.959	0.026	0.265
		n	68	68	68	66	43	43	70	67	66	68
	PostNon WORD	r	**-.255***	-0.056	0.113	0.012	-0.192	**-.349***	-0.150	-0.112	-0.202	-0.156
		Sig.	0.038	0.646	0.357	0.923	0.218	0.020	0.217	0.360	0.106	0.198
		n	67	69	69	66	43	44	69	69	65	70

Note: **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

APPENDIX 4

Table 23. Correlation matrix between Pretest Accuracy and Pretest RT scores.

PRETEST		CUBE RT	SHAPE RT	3DIS RT	WORD RT	NonWORD RT
CUBE Accuracy	Correlation	0.456**	0.424**	0.340**	0.023	0.014
	r	0.000	0.000	0.028	0.859	0.912
	n	67	67	42	65	65
SHAPE Accuracy	Correlation	0.459**	0.458**	0.248	0.040	0.051
	r	0.000	0.000	0.118	0.757	0.692
	n	66	66	41	64	64
3DIS Accuracy	Correlation	0.478**	0.071	0.193	0.093	0.273
	r	0.002	0.670	0.228	0.581	0.103
	n	44	43	43	41	41
WORD Accuracy	Correlation	0.298**	0.124	0.296	-0.115	0.087
	r	0.018	0.336	0.068	0.370	0.500
	n	65	65	40	65	65
NonWORD Accuracy	Correlation	0.388**	0.407**	0.251	0.035	0.169
	r	0.002	0.001	0.123	0.788	0.189
	n	64	64	39	64	64

Notes: **. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
Notes: Accuracy and RT are computed based on a composite of Hits and Correct Rejection

Table 24. Correlation matrix between Posttest Accuracy and Posttest RT scores.

POSTTEST		CUBE RT	SHAPE RT	3DIS RT	WORD RT	NonWORD RT
CUBE Accuracy	Correlation	0.402**	0.368**	0.055	0.271**	0.192
	r	0.001	0.002	0.745	0.028	0.125
	n	69	68	42	67	67
SHAPE Accuracy	Correlation	0.400**	0.575**	0.111	0.187	0.195
	r	0.001	0.000	0.512	0.136	0.122
	n	68	68	41	66	66
3DIS Accuracy	Correlation	0.182	0.309*	-0.123	0.129	0.231
	r	0.261	0.055	0.456	0.421	0.146
	n	40	39	41	39	39
WORD Accuracy	Correlation	0.322**	0.360**	-0.130	0.226	0.202
	r	0.009	0.004	0.443	0.066	0.104
	n	68	67	43	69	69
NonWORD Accuracy	Correlation	0.160	0.240*	-0.058	0.233*	0.122
	r	0.202	0.056	0.734	0.058	0.329
	n	67	66	43	68	68

Notes: **. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
Notes: Accuracy and RT are computed based on a composite of Hits and Correct Rejection

APPENDIX 5

Table 25. Summary of all LB and VS results.

			Baseline Means		Posttest Compared to Baseline Means		Posttest Compared to nRDs Means		Change				Best Change	
			Young RD	Older RD	Young RD	Older RD	Young RD	Older RD	RD	nRD	Overall RD	Overall nRD	Young RD	Older RD
LB		IQ			Went up	Went up			Largest drop (-)		Largest (+)		Largest (FIQ)	Largest (VIQ)
		WRAT			Went down (read), went up (spell)	Went up (read), went down (spell)			Largest (+)		Largest (+)			Largest (+) Reading
	Accuracy	WORD		2nd to highest	Went down	Went down		2nd to highest		Largest		Largest		
		NonWORD			Went down	Went down		2nd to highest		Higher				
	RT	WORD	Slower	Slower	Faster	Slower	Slower	Slower	Largest drop (-)		Largest drop (-)		Larger speed change (-)	
		NonWORD	Slower	Slower	Faster	Faster	Slower	Slower	Largest drop (-)				Larger speed change (-)	
	Dprime	WORD			Went up	Went up	2nd to highest			Largest		Largest		
		NonWORD	2nd to highest		Went up	Went up		2nd to highest		Largest				
	BETA	WORD	Highest (but -)		Went up	Went down	Highest (-)			Largest		Largest drop (-)		
		NonWORD	2nd highest (but -)		Went up	Went down	2nd highest (-)		Largest (+)				Largest (+)	
TOTAL Results LB			1/10 tasks 10%	0/10 tasks	8/10 ups and fast 80%	6/10 tasks and fasts 60%	1/10 tasks 10%	0/10 tasks	5/10 tasks 50%	5/10 tasks 50%	3/6 categories 50%	3/6 categories 50%	4/10 tasks 40%	2/10 tasks 20%

Notes: This table is to be read as the result of RDs compared to nRDs. Spots have been 'greyed' where RDs performed the lower or the lowest compared to nRDs. The use of the word "2nd" signifies that RDs were right behind nRDs who were the highest, this was not counted in the percentages. The use of the symbols "-" or "+" is an indication of the direction of the sign of the result yielded. Thus in change scores, the change may be wide, but it can be so in increase or in decrease, which has a different meaning depending on the type of task considered.

Table 25. Continued.

			Baseline Means		Posttest Compared to Baseline Means		Posttest Compared to nRDs Means		Change				Best Change	
			Young RD	Older RD	Young RD	Older RD	Young RD	Older RD	RD	nRD	Overall RD	Overall nRD	Young RD	Older RD
VS		PIQ			Went up	Went up	2nd to highest		Highest (+)		Larger (+)		Larger (+)	
	Accuracy	CUBE		2nd to highest	Went up	Went down		2nd to highest	Higher (-)					Larger drop (-)
		SHAPE		2nd to highest	Went up	Went down		2nd to highest	Higher (-)			Larger	Larger drop (-)	
		3DIS		2nd to highest	Went up	Went up		2nd to highest	Higher (+)					Larger drop (-)
	RT	CUBE	Fastest		Faster	Faster	Fastest		Higher (-)					Larger speed change (-)
		SHAPE		Fastest	Faster	Faster	Fastest		Higher (-)		Larger (-) Meaning smaller at post		Larger speed change (-)	
		3DIS	2nd Fastest		Faster	Faster				Higher (-)				
	Dprime	CUBE	2nd to highest (-)		Went down	Went down	2nd to highest (-)		Higher (-)					Larger drop (-)
		SHAPE			Went up	Went up		2nd to highest (+)	Higher (+)		Larger (-) Meaning smaller at post		Larger (+)	
		3DIS		2nd to highest (+)	Went down	Went up	2nd to highest (-)	Highest (+)		Higher (-)				
	BETA	CUBE	Highest (+)		Went down	Went down		2nd to highest (+)	Higher (-)				Larger drop (-)	
		SHAPE	2nd to highest (+)	Highest (+)	Went down	Went down			Higher (-)		Larger (-) Meaning smaller at post			Larger drop (-)
		3DIS		2nd to highest (+)	Went up	Went down	Highest (+)			Higher (-)				
TOTAL Results VS			2/13 tasks 6.15%	2/13 tasks 6.15%	9/13 ups & fast 69.2%	7/13 tasks & fasts 53.8%	3/13 tasks 23%	1/13 tasks 7.6%	10/13 tasks 76.9%	5/13 tasks 38.4%	4/5 categories 80%	1/5 categories 20%	5/13 tasks 38.4%	5/13 tasks 38.4%
TOTAL results whole study			3/23 tasks 13%	2/23 tasks 8.69%	17/23 ups 73.9%	13/23 ups 56.5%	4/23 tasks 17.39%	2/23 tasks 8.69%	15/23 tasks 65.2%	3/23 tasks 13.04%	7/11 categories 63.6%	4/11 categories 13.3%	9/23 comparisons 39.13%	7/23 comparisons 30.43%

Notes: Result to be read as RDs compared to nRDs. The word "2nd" signifies that nRDs were higher. The symbols "-" or "+" indicate the results' direction.

APPENDIX 6

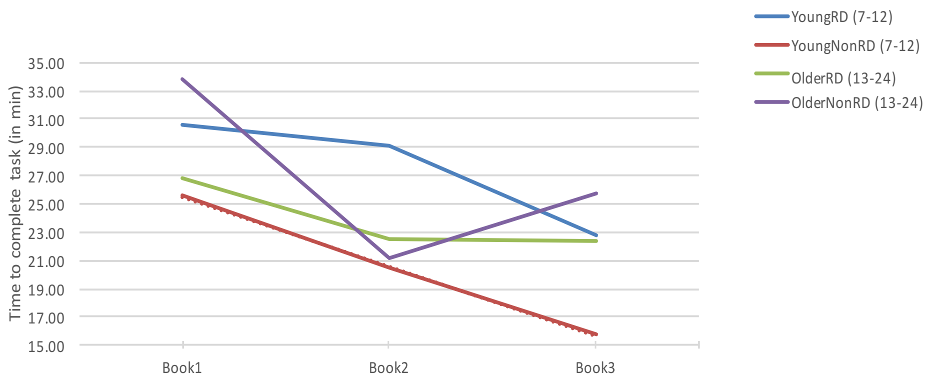


Figure 24. Mean score of book Tangrams task across time.

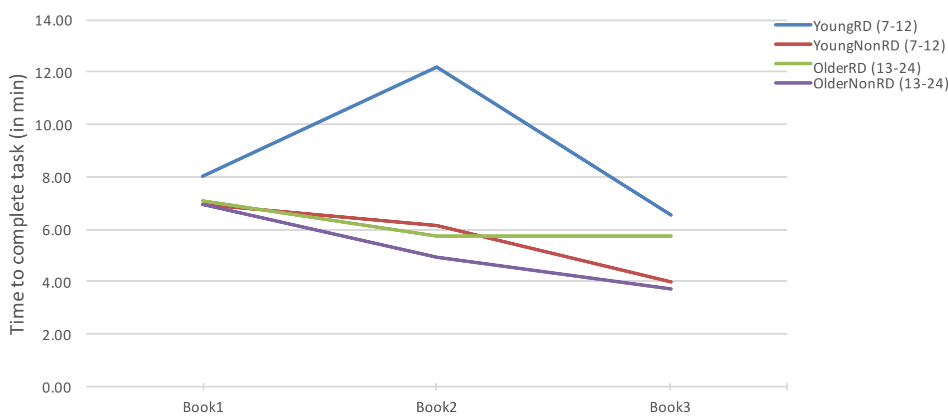


Figure 23. Mean score of book Legos task across time.

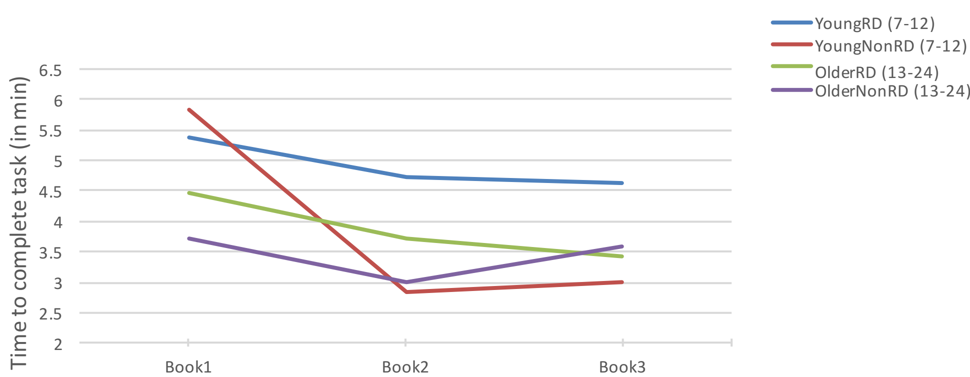


Figure 24. Mean score of book WT task across time.

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