Literacy Studies: Perspectives from Cognitive Neurosciences, Linguistics, Psychology and Education

Asaid Khateb
Irit Bar-Kochva *Editors*

Reading Fluency

Current Insights from Neurocognitive Research and Intervention Studies

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Literacy Studies

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While language defines humanity, literacy defines civilization. Understandably, illiteracy or difficulties in acquiring literacy skills have become a major concern of our technological society. A conservative estimate of the prevalence of literacy problems would put the figure at more than a billion people in the world. Because of the seriousness of the problem, research in literacy acquisition and its breakdown is pursued with enormous vigor and persistence by experts from diverse backgrounds such as cognitive psychology, neuroscience, linguistics and education. This, of course, has resulted in a plethora of data, and consequently it has become difficult to integrate this abundance of information into a coherent body because of the artificial barriers that exist among different professional specialties. The purpose ofthis series is to bring together the available research studies into a coherent body of knowledge. Publications in this series areof interest toeducators, clinicians and research scientists in the above-mentioned specialties. Some of the titles suitable for the Series are: fMRI, brain imaging techniques and reading skills, orthography and literacy; and research based techniques for improving decoding, vocabulary, spelling, and comprehension skills.

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Foreword: Prof. Zvia Breznitz 1945–2014

This book is dedicated to the blessed memory of Prof. Zvia Breznitz, who passed away on May 18th, 2014.

Prof. Breznitz was a Full Professor at the University of Haifa. She was a neuro-cognitive scientist, specializing in researching reading and dyslexia. Her creative and innovative way of thinking and her pursuit of state-of-the-art research methods were the catalysts for the groundbreaking scientific work, for which she became internationally recognized. Her work was published in more than 80 peer-reviewed articles in leading scientific journals, in a dozen book chapters and in books she edited herself. In 2006, she published the book *Fluency in Reading: Synchronization of Processes*, in which she presented an innovative theory she termed "The Brain Asynchrony Theory". This theory proved to be a key to understanding dyslexia, its underlying factors, intervention and rehabilitation. Her work had a tremendous impact on the understanding of normal and impaired processes of reading and on other aspects of learning disabilities. In particular, she contributed to the acknowledgement of reading fluency as a central component defining reading ability and to the understanding of the neurocognitive processes contributing to it as well as to the development of methods to enhance fluent reading. In recognition of her scientific contributions, Prof. Breznitz received various international fellowships and awards such as the Fogarty Fellowship at the Laboratory for Developmental Psychology, National Institute of Mental Health (NIMH), USA; she was a Distinguished Fellow at the IDEA Center in Frankfurt, Germany; a CRNS Distinguished Fellow at Descartes University, France; a Fellow at the Center for Advanced Study, Collegium Budapest; and a Fellow of The Rockefeller Foundation Center in Bellagio, Italy.

Scientific research and its practical translation to educational settings characterized Prof. Breznitz's work. Before starting her academic career, she was a school teacher herself. Her BA studies were in Psychology and Physical Geography at the University of Maryland. She studied Educational Psychology for her MA degree at the University of Haifa and wrote her dissertation at the Department of Psychology at the Hebrew University of Jerusalem. In the course of the years, she headed or served as a member of several national committees advising the Ministry of

Education, the Council for Higher Education and the National Academy of Sciences on matters of early assessment, learning and learning disabilities.

Prof. Breznitz was pioneer in her understanding of the role of performance time in reading, long before reading rate was commonly used as a measure of reading ability. As early as 1983, as part of her dissertation work, under the title *The Effect of Reading Rate on Decoding and Comprehension Among First-Grade Pupils*, she discovered that time-constraints imposed on the presentation of texts led to enhanced reading performance compared to a self-paced reading condition. This finding was in sharp contrast to the common practices at that time, which encouraged slow processing of the printed word, and particularly in reading disabled children. The same finding, which was then repeated in different works, was consequently termed "The Acceleration Phenomenon".

This discovery turned out to be central to her work: She dedicated much of her studies to the unveiling of the underlying factors of this phenomenon and developed an innovative computerized reading-training program which imposed time-constraints on reading. The "Reading Acceleration Program" (RAP) has been extensively studied in children and adults and in speakers of different languages and readers of different orthographies, both in her laboratory and in laboratories outside Israel. The program had shown positive and sustainable effects on reading performance across languages and orthographies, indicating that she had discovered a remediation technique addressing universal aspects of reading disability. Some aspects of her work on this issue have recently been published in the leading scientific journal "Nature", and further studies on the effects of this program are presented in this book.

Prof. Breznitz's compassion for the less fortunate was a guiding light for her. A unique characteristic of the training method she developed is that it can be easily implemented in school settings and does not require the mediation of a tutor. Highly important to her in the process of developing the program was the aim of reducing the financial load on families of learning disabled children and of providing equal opportunities for populations from various backgrounds. These considerations also guided her efforts to develop and implement assessment batteries in Hebrew and Arabic, which can be administered in class settings in schools.

Prof. Breznitz was a natural leader and a visionary. To mention only a few of her achievements, she was one of the first to introduce research and practices in the field of learning disabilities in Israel, and in 1979, she founded the Clinical Laboratory of Learning Disabilities at the University of Haifa and was its director until the year 2007. In 1992, she founded the Laboratory for Neurocognitive Research, which she directed until her passing. In 1998, she was one of the main contributors to the establishment of the Division (currently the Department) of Learning Disability at the Faculty of Education at the University of Haifa, which she also headed until 2005. In the year 2007, she established the Edmond J. Safra Brain Research Center for the Study of Learning Disabilities at the University of Haifa, which she directed until her very last days. With the goal of promoting knowledge about the different types of learning disabilities, the Safra Center utilizes brain-based research, behavioral methods and clinical interventions to explore theories and practices in the field. Acknowledging the unique variety of the population in Israel, the study of learning disabilities in the Arabic-speaking population and in populations of bilinguals became, through her great support, an integral part of the activities of the Safra Center. Thanks to her tireless commitment, and to the generous support of the Edmond J. Safra philanthropic Foundation, she recruited faculty members to promote research in different fields related to learning disabilities, including reading and writing and their development in the Arabic and Hebrew languages, bilingualism, attention and numerical cognition.

Prof. Breznitz was a teacher and mentor of several dozens of students, and many of them carried out research under her supervision. Her great energy and enthusiasm for research on learning and learning disabilities attracted many students to her laboratory, which worked constantly at full capacity. She expressed scientific openness and was willing to attend to new ideas, explore new fields of research and methods and combine the students' personal interests with her expertise. This led to an interesting work environment of great diversity in subjects of research and work-practices.

On a more personal note, Prof. Breznitz cared about the academic work of her many students as much as she cared about their personal well-being, thereby giving the work environment a family atmosphere. She accompanied her students in good times and in bad. She did not settle with being a "good listener" to the problems of others, but actively tried to help whoever turned to her, and was particularly happy when hearing that one of her students extended his family or travelled to interesting places around the world. Prof. Breznitz was also my (Dr. Bar-Kochva, the second editor of this book) mentor for almost 10 years, while completing my Master's and PhD degrees. Scientific curiosity, the determination in pursuing scientific goals, being scientifically relevant and innovative, as well as the importance of linking scientific work with the needs of the society are but a few of the many things I learned from her.

Prof. Asaid Khateb (the first editor of this book) was a colleague of Prof. Breznitz. Their acquaintance began when he was a researcher at the Laboratory of Experimental Neuropsychology at the Geneva University Hospitals, where he conducted neurocognitive research on language processing and bilingualism. Being determined and proud to promote research on reading in the Arabic language, Prof. Breznitz invited him to join the faculty staff at the Edmind J. Safra Brain Research Center for the Study of Learning Disabilities. Upon his arrival, she provided all that was necessary to make him feel at home and from his very first day she charged him with various academic responsibilities letting him feel that he had always belonged there. On a very regular basis, she shared new ideas and new research projects she considered worth investigating with him. In this regard, Prof. Khateb also admits that, thanks to Prof. Z. Breznitz' spirit, he is currently involved in very exciting fields of research.

For this and for reasons too numerous to name, both editors of this book are very grateful to Prof. Breznitz, and hope to continue in the path she paved for us. We both have had a great opportunity to have known such a unique person with a rare mind and an enormous heart. She is missed terribly, both personally and professionally.

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Introduction

Irit Bar-Kochva, Asaid Khateb, and R. Malatesha Joshi

Reading is a complex procedure, involving a variety of cognitive and language skills which have to be well integrated in order to allow efficient reading (Breznitz, 2006). While in most cases this process is successful, high prevalence of reading failure is reported in literate societies (5–10 % of the population). The study of reading disability has historically focused on accuracy in reading, typically resulting from a difficulty in phonological processing (Lyon, Shaywitz, & Shaywitz, 2003). However, the last decade has seen a considerable shift in the manner in which reading failure is understood, and it is now recognized that dysfluent reading is an additional and important characteristic of reading disability (Lyon et al., 2003). This difficulty is evident even after many years of print exposure and remedial teaching (Breznitz, 2006). Breznitz in her works has even put forward the idea that fluency lies at the core of reading disability and its manifestation.

Different definitions of fluency in reading have been proposed, which share the basic idea that it reflects effective reading, with performance time being a central

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factor. It was suggested to consist of the ability to read texts quickly and accurately, effortlessly and with good understanding (Report of the National Reading Panel, 2000; Meyer & Felton, 1999; Schreiber, 1980; Wolf, Bowers, & Biddle 2000). Others have extended the definition to include appropriate prosody (Hudson, Mercer, & Lane, 2000). Another line of definitions refers to achieving automaticity in the underlying skills of reading and their proper integration (Hudson, Pullen, Lane, & Torgesen 2009; Perfetti, 1985; Wolf & Katzir-Cohen, 2001). Considering that fluency in reading involves almost any aspect of reading, it may be of no surprise that it has been suggested to be the hallmark of skilled reading (Lyon et al., 2003).

1 Reading in Different Languages and Orthographies

Research on reading had focused for many years on the study of the English orthography. The English orthography, however, is an extreme case of spelling-sound ambiguity, and has even been termed as an "outlier" orthography (Share, 2008). Consequently, it may impose unique demands of processing on its readers. Other orthographies, however, read by millions of people around the world, differ not only in the transparency of their spelling-sound relations, but also in many other aspects: from the very basic principles according to which the oral language is transcribed (e.g., alphabetic/logographic), the linguistic structure of the language and the manner in which it is conveyed in writing (e.g., phonology and morphology), to the visual features of the writing system (e.g., Latin, Hebrew, Arabic letters).

Considerable body of evidence has been accumulated to indicate that while there are many common aspects to the reading of different orthographies, there are also some important orthographic-specific aspects. Differences between readers of different languages and orthographies have been found in the pace at which reading is acquired, in the processes involved in reading and in the cognitive demands imposed on the readers (Frost, 2005; Katz & Frost, 1992; Seymour, Aro, & Erskine, 2003; Ziegler & Goswami, 2005; Ziegler et al., 2010). Of particular interest to the topic of this book is the role of fluency in reading in the manifestation of reading disability in readers of different orthographies: while reading disability in readers of orthographies with opaque spelling-sound relations is expressed in inaccurate reading, readers of transparent orthographies often achieve accurate reading, their fluency, however remains impaired (Wimmer, 1993).

2 Purpose

The goal of this volume is to present recent advances in the study of fluency in reading. Two questions are at the center of this book: (1) What is the cognitive and neurocognitive basis of fluent reading and (2) How can fluency in reading be improved. The book comprises two parts, one addressing each of these questions. In the first part, recent data are presented on brain systems supporting fluency in reading and their functional characteristics in different populations of readers and age groups. In addition, data based on cognitive-behavioral studies exploring the cognitive and language skills involved in fluent reading are presented. In the second part, examinations of training programs designed to enhance fluency in reading are reported, and the underlying mechanisms trained in these programs are considered.

While taking into account the need to explore reading in languages other than English, the book provides a unique multi-lingual perspective on reading research by including studies of readers of different orthographies and speakers of different languages. In addition to data on English readers, the first part of the book includes evidence on brain activation in readers of Chinese and Spanish (Jasinska et al.). Moreover, as the majority of the world speaks multiple languages, reading in bilingual populations is also considered in this chapter. Brain-imaging data and behavioral data from Hebrew readers are also included (Horowitz-Kraus; Lipka, Katzir, & Shaul). In the second part of the book, intervention studies in readers of German (Nagler, Lindberg & Hasselhorn) Spanish (Escribano) and Finnish (Aro & Lyytinen), are reported. The orthographies explored in both parts of the book differ from the English orthography in many aspects, and may therefore suggest universal characteristics of reading on the one hand, and on the other hand provide an insight into language–specific aspects of reading.

3 The Chapters in This Volume

Reading is basic for survival and thus, reading problems have an impact on progress of individuals, societies, and nations. Naturally, aspects related to reading development and reading problems are studied by various disciplines such as neurosciences, genetics, speech and hearing sciences, linguistics, psychology, and education. The results from these various disciplines have shown that reading problems may be caused by genetic factors or environmental influences or a combination of the two. Even though research studies have been conducted relating to reading problems from diverse disciplines, there has not been a concerted effort to present the findings together. Irrespective of the source of the reading problems, early identification of reading problems and a systematic instruction based on scientific evidence would help in improving reading. The chapters in this volume address this important issue of the nature of reading problem and explore plausible techniques to overcome the reading problem. Additionally, as Share (2008) pointed out, most of the studies on reading are based on the model of English reading, perhaps due to the fact that there are more studies conducted in English speaking countries and published in English journals. We definitely need research results from orthographies that are different from English orthography both in terms of writing system as well as orthographic depth. While reading involves various subcomponents, such as, alphabetic principle, decoding, sight word knowledge, vocabulary, syntax, working memory, and comprehension, one of the important subcomponents that has received much attention in the last two decades is the concept of fluency, which includes aspects of speed, accuracy and, according to certain definitions, also prosody. Improvement in one subcomponent may directly or indirectly affect the improvement of another subcomponent. Zvia Breznitz's contribution on how to improve fluency using the Reading Acceleration Program (RAP) she developed had a remarkable influence on improving reading and this volume highlights some of the findings based on her innovative idea.

Katzir, Christodoulou, and Chang begin the volume by presenting recent research from cognitive neuroscience and genetics. The chapter outlines the neural circuit mechanism among typically developing readers and among individuals exhibiting dyslexia-type symptoms and the genetic influence as a marker for reading difficulty. What happens when part of the brain is underdeveloped because of genetic influence? The authors present results from studying individuals who had periventricular nodular heterotopia (PNH), which is a neuronal migration disorder caused by genetic mutations. They found that among PNH patients, fluency and phonological processing was affected and improving these skills may improve reading.

Continuing with the role of neurological mechanism in reading, Jasinska et al., offer evidence in the neural circuitry of readers of various levels. They rightly point out the various skills of phonology, morphology, and orthography needed to master reading skills. These skills are generally performed by left-hemisphere frontal, temporoparietal and occipitotemporal cortical regions and emphasize the role of the Visual Word Form Area (VWFA) in phonological processing. Interestingly, they found similar pattern in different orthographies such as Chinese. Continuing with the discussion of similarities and differences among different orthographies, the authors also deliberate about what happens when two languages are acquired simultaneously or are acquired in a sequential manner. Certainly more research is needed on this topic.

Horowitz-Kraus, in the next chapter, explains 'executive functions', its role in reading development, and how executive functions can be improved through the 'Reading Acceleration Program' (RAP) and thus improve reading. Executive functions include aspects of attention, inhibition, working memory, and speed of processing. The author outlines how children and adults with dyslexia show impairment in executive functions including speed of processing. The chapter presents the results for a study of training individuals with reading problems through RAP. The author reports the improvement in executive functions and reading and interestingly, the concomitant changes in the neural circuitry in the brain.

As mentioned earlier, fluency consists of speed, accuracy, and prosody. While speed and accuracy in reading have been studied, there are not many studies examining specifically the role of prosody in reading. The chapter by Ashby presents evidence for the important role prosody plays in developing fluency in reading through eye-tracking experiments. Ashby outlines progression of fluency development through the stages of initial development, interim phase and final full fluency and how the neural circuitry changes accordingly in each of these stages.

Additionally, Ashby also discusses the changes in fixation of eye movements during reading through eye-tracking experiments. Like many other studies, most of the experiments have been conducted on English-speaking individuals. Certainly, studies from other orthographies are necessary.

In their chapter, Lipka, Katzir and Shaul examine the development of fluency in reading and its underlying skills during the first grade in children learning to read the transparent Hebrew orthography. A rapid growth in fluency in reading during the first year of schooling is reported, and the variance in this measure of reading was explained by phonological awareness and speed of processing. Their results highlight the need to follow closely the proper development of fluency in reading and its underlying skills early on in children learning to read a transparent orthography.

Breznitz's Acceleration Phenomenon (AP) has been studied widely in the area of reading, but is the phenomenon applicable to arithmetic? This was one of the questions raised by Nagler, Lindberg, and Hasselhorn. The chapter intially discusses the research findings relating to the success of AP in improving reading and then describe the results of their experiment in applying the acceleration procedure to learning arithmentic among third grade students. The authors used mental arithmetic tasks including multiplication and advanced addition tasks to test the utility of the acceleration procedure. The results showed that for multiplication tasks, calculating errors and the processing time decreased in an accelerated presentation condition compared to a self-paced condition, while there was no such effect in the addition tasks. The authors intrepet their findings as that fading manipulation did not affect procedural-related addition tasks but was helpful while performing retrieval-related multiplication tasks. Additional data is provided from reading studies, suggesting a fact retrieval account of the AP.

As mentioned earlier, studies are needed in order to examine reading and its intervention in different orthographies that vary on orthographic depth. Finnish orthography is considered one of the highly transparent orthographies with a very close correspondence between graphemes and phonemes. Aro and Lyytinen describe the nature of Finnish orthography and then explain a computerized game called '*Ekapeli*', (referred to as *Graphogame* outside of Finland). *Ekapeli* is used in all of the elementary schools in Finland and has been attributed to the high success rate of school children in Finland based on international assessments like PISA and PIRLS. Trial demonstrations have been conducted using *Grophogame* in different countries and orthographies, and waiting for more controlled studies from different laboratories.

Similar to Finnish, Spanish orthography is also a fairly regular orthography with relatively simple grapheme-to-phoneme correspondences. Thus, the major problem of Spanish-speaking children in reading acquisition is speed of processing more than accuracy. Exploiting this phenomenon, Escribano, describes a preliminary study using the Reading Acceleration Program (RAP) among six grade 4 and six grade 6 children. After twenty sessions of using the RAP, it was found that reading rate improved among good comprehenders and reading comprehension increased among poor comprehenders. Additionally, there was an improvement in rate of decoding, speed of verbal processing (RAN) and visual attention (Symbol Search).

In summary, these chapters point out that reading disability is not a homogeneous condition but should be seen as a continuum and that there are different kinds of reading problems. Additionally, the chapters call attention for further research especially relating to reading development in different orthographies and among bilinguals. Considering the majority of the world's population consists of bilinguals, if not multilinguals, more research is needed with bilingual children, both with simultaneous bilinguals – those who acquired two languages at the same time and sequential bilinguals – those who acquired two languages at different time periods. Even though various subcomponents of reading may affect reading acquisition, one of the important subcomponents is fluency, which includes speed, accuracy and prosody. Improving fluency in reading by the Reading Acceleration Program devised by Breznitz can have a lasting impact on reading acquisition. Further, accelerated program may also be helpful in certain arithmetic problem solving as well. We must salute Prof. Zvia Breznitz for her theoretical and applicable scientific achievements, which contribute tremendously to our ability to help children in various parts of the world.

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Part I
The Cognitive and Biological Basis of Fluency Related Processes

The Neurobiological Basis of Reading Fluency

Tami Katzir, Joanna A. Christodoulou, and Bernard Chang

Abstract This chapter shall provide an overview of reading fluency research in the past two decades. We will first discuss fluency deficits and then discuss the genetic and brain behavior activation patterns associated with reading fluency deficits in individuals with dyslexia. Finally, we will present data from special abnormal populations with a specific fluency deficit.

Keywords Dyslexia • Fluency • Malformations • Genetics • Reading • Periventricular nodular heterotopia

1 Introduction

To most of us, the act of reading seems as natural and automatic as driving. We read effortlessly and rapidly. We read to learn new information or review familiar material. For many of us, reading itself is one of the greatest pleasures available. For a significant number of children, however, learning to read is similar to deciphering a highly enigmatic code. It is estimated that 5–17 % of the population, despite having adequate intelligence and schooling, has some type of reading disability. This population is typically referred to as having developmental dyslexia, which is the

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most common reading disability. Defining features include difficulties in accurate and/or fluent word reading. Alternatively, struggling readers who can read single words without difficulty can show challenges instead in connected text reading fluency or comprehension (Georgiou, Das, & Hayward, 2009; Katzir et al., 2006). The Diagnostic and Statistical Manual of Mental Disorders (DSM-5) subsumes reading disabilities under the diagnostic label of Specific Learning Disorder (SLD). SLD includes disabilities in reading accuracy, fluency, or comprehension; spelling; written expression; or mathematics reasoning (American Psychiatric Association [APA], 2013). The formal diagnostic definition for Specific Learning Disorder is summarized as follows:

> Difficulties in learning and using academic skills, as indicated by the presence of at least one symptom … that have persisted for at least 6 months, despite the provision of interventions that target those difficulties. The affected academic skills are substantially and quantifiably below those expected given the individual's chronological age, and cause significant interference with academic or occupational performance, or with activities of daily living. The learning difficulties begin during school-age years but may not become fully manifest until the demands for those affected academic skills exceed the individual's limited capacities. The learning difficulties are not better accounted for by intellectual disabilities, uncorrected visual or auditory acuity, other mental or neurological disorders, psychosocial adversity, lack of proficiency in the language or academic instruction, or inadequate educational instruction. When more than one academic domain is impaired, each one should be coded individually. For example, when reading is impaired, one must specify if the deficit is in word reading accuracy, reading rate/fluency, or reading comprehension (APA, 2013, p. 66–67).

According to the DSM-5, Dyslexia is an alternative term used to refer to a pattern of learning difficulties characterized by problems with accurate and/or fluent word recognition, poor decoding and poor spelling abilities. When using this term, it is important also to specify any additional difficulties presented, such as difficulties with reading comprehension or math reasoning (APA, 2013, p. 67).

Most notably, in comparison to previous versions of the DSM, the current definition puts a distinct emphasis on reading fluency. Reading fluency has been defined as "a level of accuracy and rate where decoding is relatively effortless…and where attention can be allocated to comprehension" (Wolf & Katzir-Cohen, 2001, p. 219). It is debated whether reading fluency difficulties are independent from or a consequence of difficulties in reading accuracy (Breznitz, 2006; Chang et al., 2007; Katzir, Kim, Wolf, Morris, & Lovett, 2008).

In this chapter, we compare two clinical groups of readers that reveal distinct perspectives on reading fluency: readers with developmental dyslexia and individuals with periventricular nodular heterotopia (PNH). This latter group shows distinct difficulties in reading fluency concomitant with a specific brain malformation of cortical development that is associated with seizures. These reader groups can offer a unique perspective into the necessary and sufficient anatomical and functional characteristics of the brain to support fluent reading.

We present current cognitive and neuroscientific findings in reading disabilities research based on these reader groups as they inform our understanding of reading fluency. We will conclude by suggesting that a comparison across groups holds the promise of revising current models of reading development and reading difficulties. Most importantly, understanding the different pathways to development and breakdown of reading fluency in the reader groups will serve as an important steppingstone toward the assessment and remediation of these problems in diverse populations with developmental disabilities.

2 Background on Reading Disabilities: Epidemiology and Heritability

Reading is a dynamic skill that depends on both exposure and brain maturation. A recent longitudinal study among children with typical reading skills revealed links between cortical volume and componential reading skills in rapid naming, word reading accuracy and fluency in reading (Houston et al., 2014). Volume reductions in the left parietal and frontal cortical brain regions over time are associated with better performance on rapid naming, word reading and fluency. This finding suggests that cortical circuits that are tuned and efficient over time are associated with stronger reading skills.

Developmental dyslexia is best described as a heterogeneous group of disorders, with several underlying explanations for distinct subtypes of reading disabled students (Katzir, 2001). Dyslexia is both heritable and familial. Family history is one of the most important risk factors; 23–65 % of children who have a parent with dyslexia are also identified with reading difficulties. The percentage of dyslexic siblings out of all children identified with dyslexia is approximately 40 % (see Shaywitz & Shaywitz, 2005, for a further review). The variance of reading skills explained by genetic factors is high, with heritability estimates ranging from 40 to 80 % (Schumacher, Hoffmann, Schmäl, Schulte-Körne, & Nöthen, 2007).

The rates of heritability and identification rates in dyslexia remain inconsistent. Barbiero et al. (2012) identified prevalence rates of dyslexia in Italian speaking children aged 8–10 to be around 3 %. In another study of English speakers, prevalence of dyslexia was found to be 9 % among school-aged children (aged 8–17) and even 28 % among participants from selected families with one member already suffering from dyslexia. Other findings indicated that when one of the parents is dyslexic, 22–35 % of the children are affected too (Saviour, Padakannaya, Nishanimutt, & Ramachandra, 2009). In summary, while there is agreement that dyslexia is a neurological condition with some genetic basis, there is great variation in reports of prevalence and heritability of dyslexia. These may be related to the identification measures used, language spoken in the study and age of the children included in the sample. Thus, while significant advances have been made at understanding the brain, behavioral and genetic basis of dyslexia, there is not yet a clear universal genetic marker that is agreed upon for the phenomenon.

The prominent theory of the cause of dyslexia affirms common clinical observations of educators and psychologists that many children who cannot read have deficits in the phonological processing system. Phonological processes are those involved in the representation, analysis, and manipulation of information specifically related to linguistic sounds from the level of the individual speech sound, or phoneme, all the way to the level of connected text. That is, children with dyslexia have difficulty developing an awareness that words, both written and spoken, can be broken down into smaller units of sounds, such as phonemes, onsets, rhymes and syllables (Wolf & Kennedy, 2003).

Neuroimaging work has provided converging lines of evidence in support of the phonological deficit theory. Neurofunctional research has shown that a deficit in integrating letters and speech-sounds among readers with dyslexia is one of the proximate causes of reading and spelling failure (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009) and it may bridge the gap between phonological processing deficits and problems in learning to read (Burman & Booth, 2006). A considerable body of evidence indicates that dyslexic readers exhibit disruption primarily, but not exclusively, in the neural circuitry of the left hemisphere serving language (see Houston et al., 2014, for review).

A neuroimaging study using functional magnetic resonance imaging (fMRI) (Hoeft et al., 2007) measured brain activation during a word rhyme judgment task and gray matter morphology in dyslexic adolescents, and compared the results to the results of an age-matched group and a reading-matched group younger than the dyslexic group. Results showed that hyper-activation in frontal and sub-cortical brain regions was related to current reading ability, independent of dyslexia, while hypo-activation in left posterior regions was related to dyslexia itself. Furthermore, one of the brain regions that exhibited hypo-activation in dyslexia, the left inferior parietal lobe (IPL), also exhibited a reduction of gray matter in dyslexia. This study distinguished between regions associated with dyslexia specifically (posterior regions) and those recruited for groups of lower reading competence relative to a stronger reading group (frontal regions).

Another fMRI study demonstrated hemispheric activation differences between dyslexic readers and typical readers during lexical decision tasks (regular words, irregular words, pseudo-words) (Waldie, Haigh, Badzakova-Trajkov, Buckley, & Kirk, 2013). Specifically, the results showed hypo-activation in the left posterior areas and over-activation in the right hemisphere among dyslexic readers. This study highlighted the reliance of struggling readers on a right hemisphere system that serves a compensatory role.

Reduced activation in left hemispheric networks (including parieto-temporal and occipito-temporal regions) during phonological processing among readers with dyslexia already exists in young pre-literate children with familial risk for dyslexia (Raschle, Zuk, & Gaab, 2012). Brain activity within those brain regions shows a positive correlation with phonological processing skills among children with or without familiar risk for dyslexia. This study suggests that children's functional systems tuned to language sounds can be vulnerable before reading instruction given familial history, though the percent of children who go on to have difficulties remains undetermined.

Qualitative and quantitative work by educators and psychologists has led to the extension of the phonological deficit view of dyslexia and broadened our understanding and treatment of reading disorders. Inevitably, in a process as complex as reading, reductionist hypotheses cannot explain all sources of reading difficulty. Some children elude diagnosis, classification, and sometimes treatment. Subtyping classification represents not a new, but rather an ongoing, effort to address the heterogeneity of reading disabled populations and to understand children who do not fit conventional theories of breakdown. Such research differs from those on reading disabilities which tacitly or explicitly operate within a model of general homogeneity, i.e., where single factors are assumed to explain reading failure (Badian, 1997; Carver, 1997; Kirby, Parrila, & Pfeiffer, 2003; Lovett, 1987; Lovett, Steinbach, & Frijters, 2000; Manis, Doi, & Bhadha, 2000; McGrath et al., 2011; Wolf & Bowers, 1999).

Current research in cognitive neuroscience has complemented behavioral work extending beyond phonological processing deficits as explanatory frameworks for reading disabilities. Naming speed deficits are considered to be an alternative and a complement to phonological deficits (Jones, Branigan, & Kelly, 2009; Wolf & Bowers, 1999). That is, impaired readers are slow to retrieve the names of very familiar letters and numbers. A naming speed deficit reflects difficulty in the processes underlying the rapid recognition and retrieval of visually presented stimuli. Debate exists whether rapid letter naming is a kind of phonological processing task, or whether it taps additional cognitive and linguistic processes that are not accessed within phonological processing tasks (Wagner, Torgesen, & Rashotte, 1999), supporting the notion that phonological and naming-speed deficits are independent factors, each contributing separately to reading development. A growing body of research demonstrates that there are discrete groups of children with reading disabilities characterized by either naming-speed or phonological processing deficits, or by combined deficits in both areas (Araújo, Pacheco, Faísca, Petersson, & Reis, 2010; Badian, 1997; Compton, DeFries, & Olson, 2001; Manis et al., 2000; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007; Wolf & Bowers, 1999).

Advances in neuroimaging techniques offer the opportunity to investigate the neuroanatomical systems that are engaged in rapid serial letter- and word-reading. These techniques may provide insight into lines of evidence for the role and relationship between neural structures involved in rapid naming and reading. A study using fMRI suggests that the same factors that are related to the connections of visual representations to phonological information are also activated in rapid letter recognition (Misra, Katzir, Wolf, & Poldrack, 2004). In this study, a collaborative team of neuroscientists and educators used the theoretical framework suggested by Wolf and Bowers (1999) and applied it to neuroimaging research in skilled readers. They found that in skilled readers, the neurological underpinnings of phonological processing and rapid letter naming differ. These findings suggest that phonological processing and rapid letter naming are discrete cognitive processes that have different relationships to reading.

In a study of the neural correlates of reading fluency, the findings of Christodoulou et al. (2014) offer a hypothesis for reading fluency deficits in dyslexia. Specifically, brain regions involved in semantic retrieval and semantic representations failed to be fully engaged for comprehension at rapid reading rates in adults with dyslexia. This finding is consistent with patterns of hypoactivation for posterior brain networks in dyslexia for reading words. This work has expanded our understanding of neural systems supporting reading by identifying atypical recruitment of neural systems and correlates with reading behaviors in dyslexia.

In summary, a range of neurobiological investigations, examining multiple linguistic and cultural groups, has documented the intrinsic disruption of neural systems for reading and dyslexia across languages and cultures (Grigorenko 2001; Lyon, Shaywitz, & Shaywitz, 2003; Paulesu et al., 2001; Pollack, Luk, & Christodoulou 2015; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Collectively, these studies have contributed to our general understanding of the brain regions and processes involved in normal and impaired reading. A considerable body of evidence indicates that children with a reading disability exhibit both subtle structural differences as well as differences in neural circuitry when compared to non-impaired readers (Berninger & Richards, 2002). However, there is no definitive brain marker, either structural or functional, of dyslexia. Instead, these combined studies give a better picture of brain differences between normal and dyslexic readers as a group (Katzir & Pare-Balagov, 2006).

3 Dyslexia as a Disorder of Cerebral Cortical Development

There has long been evidence that dyslexia may be associated with subtle abnormalities of cortical development. In the 1980s, Galaburda and colleagues reported several developmental abnormalities in brains of patients with dyslexia, including an absence of the normal asymmetry of the planum temporale, foci of ectopic neurons in the molecular layer of perisylvian cortex, and foci of glial scarring (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Humphreys, Kaufmann, & Galaburda, 1990). Across multiple reports, subtle structural abnormalities have been seen in high-resolution imaging studies of dyslexic patients' brains, although there are few consistent, reproducible anatomical findings (Habib, 2000). Candidate genes have been identified at chromosomal loci linked to dyslexia susceptibility, and some of these encode proteins thought to be important either in axonal pathfinding or in neuronal migration during brain development (Hannula-Jouppi et al., 2005; Meng et al., 2005).

A comprehensive review regarding the genetics of dyslexia (see Scerri & Schulte-Körne, 2010) revealed dyslexia risk chromosomal loci, like DYX1, DYX2, DYX3, DYX5 and DYX8 (e.g. Chapman et al., 2004; Grigorenko et al., 2003; Marlow et al., 2003; Schumacher et al., 2008; Tzenova, Kaplan, Petryshen, & Field, 2004). A novel approach, then, to the neurobiological study of dyslexia and other learning disabilities is to investigate the phenotypes of known malformations of cortical development (MCDs), neurological disorders in which the usual process of cerebral cortical development is disrupted during embryonic and fetal life (Barkovich, Kuzniecky, Jackson, Guerrini, & Dobyns, 2005).

Given the histopathological and genetic findings described above, the study of those malformations associated with neuronal migration problems may be particularly relevant to our understanding of the relationship, if any, between dyslexia in the broad population and developmental abnormalities of the cerebral cortex.

4 Periventricular Nodular Heterotopia (PNH): A Rare Brain Malformation

Periventricular nodular heterotopia (PNH), a disorder of neuronal migration that in some cases is associated with specific genetic mutations, might provide us exclusive insights, as it is a rare disorder that is linked to focal deficits in reading fluency (Reinstein, Chang, Robertson, Rimoin, & Katzir, 2012). PNH is one of a number of DBMs, or developmental brain malformations (Barkovich et al., 2005), associated with seizures. With the advent of high-resolution neuroimaging, and in particular the widespread use of magnetic resonance imaging (MRI) in patients with epilepsy, the diagnosis of MCDs is becoming more common in clinical medicine. In fact, MCDs are now recognized to be a relatively prevalent cause of seizure disorders (Sisodiya, 2004).

During embryonic and early fetal life, progenitor cells called neuroblasts proliferate deep in the brain along the lateral ventricles, which are intracerebral spaces filled with cerebrospinal fluid. These progenitor cells divide, giving rise to cells that are destined to become cortical neurons. However, these cells must first migrate from the proliferative zones that are adjacent to the ventricles outward toward the surface of the brain in order to begin populating what will soon become the multilayered cerebral cortex. The failure of groups of neurons to migrate to their proper destination leads to misplaced, or heterotopic, regions of gray matter in the mature brain. In PNH, nodules anywhere from a few millimeters to more than one centimeter in diameter are present along the walls of the lateral ventricles bilaterally. These nodules contain neurons that are morphologically normal but appear to have failed to migrate properly to the cortical surface (Eksioglu et al., 1996; Ferland et al., 2009; Fox et al., 1998). In some cases the nodules are so large and numerous that they become confluent, forming a continuous string of gray matter along the ventricles.

Classic bilateral PNH has been associated with mutations in the Filamin A (*FLNA*) gene (Fox et al., 1998; Robertson, 2005). This gene encodes an actin-cross linking protein (filamin) that is expressed in multiple different organ systems during development and plays a critical role in cell locomotion. In the developing nervous system, it appears to be important for neuronal migration, although it may also have effects on the neuroepithelial lining of the ventricles and on the cerebral vasculature. Females with mutations in the *FLNA* gene on one of their two copies of the X chromosome typically demonstrate the classic PNH appearance on brain MRI, and can pass on the condition to 50 % of their daughters. Most mutations in *FLNA*, when passed on to sons (who have only one copy of the X chromosome), are thought to result in prenatal lethality and spontaneous abortion, although certain mutations and patterns of somatic mosaicism can result in liveborn male children who may have classic PNH or other abnormalities (Guerrini et al., 2004). Researchers have demonstrated the presence of a number of variant forms of PNH associated with abnormalities such as hydrocephalus and microcephaly; these appear to have different genetic etiologies (Sheen et al., 2004a, b).

The histopathological and genetic characteristics of PNH have been known for a number of years. Despite this, it has only been in recent years that a detailed behavioral study of PNH patients has been undertaken, and in fact it is perhaps the cognitive and intellectual abilities of PNH patients that are the most surprising aspect of this condition. Although classic PNH appears to represent a quite widespread abnormality of neuronal migration, patients with this condition have generally been found to be of normal intelligence (d'Orsi et al., 2004). In fact, most are not diagnosed until adolescence or later, when seizures develop and an MRI of the brain is obtained.

A detailed behavioral study of PNH was undertaken to test the hypothesis that the cortical developmental abnormality would result in cognitive deficits in PNH patients that could be identified by expert neuropsychological testing, but might spare performance on tests of general intelligence. This work demonstrated that heterotopia patients share similar behavioral profiles to developmental dyslexia patients (Chang et al., 2007). Both groups had impaired reading fluency and phonological processing difficulties, but only the dyslexic group had significant lower phonological processing skills compared to normal readers. There was no significant difference in IQ scores between the groups. Using diffusion tensor imaging (DTI; a noninvasive, MRI-based method that allows for analysis of white matter microstructure and visualization of fiber tracts), the researchers revealed that PNH was associated with specific, focal disruptions in white matter microstructure and organization in the vicinity of gray matter nodules. The degree of white matter integrity correlated with reading fluency in PNH patients. Hence, the degree to which long cortico-cortical fiber tracts are affected may be the factor that influences reading performance among PNH patients.

A study by Reinstein et al. (2012) has presented a mother and daughter pair who suffers from bilateral widespread gray matter heterotopia, both diagnosed with a specific mutation in *FLNA* gene and the same X-chromosome inactivation. Their results revealed different reading and cognitive profiles. Both of them had normal verbal IQ and intact phonological processing skills, but the mother had significant impairments in reading fluency and reading comprehension, whereas the daughter had no fluency or comprehension problems. The mother's profile is consistent with previous findings of impaired reading fluency and intact phonological skills among periventricular heterotopia patients (e.g., Chang et al., 2007). The unique findings of Reinstein et al. (2012) lead to the assumption that the same genetic mutation and similar heterotopia anatomy may result in different effects on cortical circuits, hence, differentiated cognitive outcomes among distinct patients.

Evidence indicates that regions of nodular heterotopia in a developmental brain malformation have connectivity to other regions of gray matter in the brain, most commonly to discrete regions of cerebral cortex that immediately overlie the heterotopia themselves (Christodoulou et al., 2012). This study identified white matter fiber tracts that appear to mediate structural connectivity between heterotopia and some brain regions, and illustrated that these regions are also highly functionally correlated, as determined by resting-state blood oxygenation level-dependent (BOLD) imaging.

Further research has provided evidence of functional brain activation within periventricular nodules in PNH participants during reading related tasks (Christodoulou et al., 2013). Standard behavioral tasks that related to reading are associated with the activation of heterotopia across multiple anatomical locations in PNH participants using a strict statistical threshold. Their results represent a systematic demonstration that heterotopic gray matter can be metabolically co-activated in PNH.

5 Clinical and Research Implications

The work described above has important implications for the clinical care of patients with developmental brain malformations. It must be recognized that even malformations felt not to adversely affect cognitive function may in fact have specific learning disabilities or other limited cognitive impairments associated with them. These would only be evident upon detailed neuropsychological assessment. In these situations, clinicians should have a low threshold for arranging detailed cognitive testing. The identification of any such disabilities may warrant the institution of early interventions in school-age children who have been diagnosed with MCDs, in addition to the medical care they may be receiving for seizures and other clinical manifestations of their brain malformation.

The results of the PNH studies also suggest that a more detailed structural study of PNH patients' brains, with particular attention to gray matter volume, cerebral cortical thickness, and white matter microstructure may prove particularly illuminating in the search for the underlying neuroanatomical basis of the reading disability in this population. These types of detailed anatomical studies can now be undertaken using computational post-processing methods applied to neuroimaging data acquired from live human subjects, a key innovation given the dearth of post-mortem brain tissue available in this and similar conditions. Detailed functional imaging studies, using BOLD functional MRI techniques, may help to shed light on the neural basis of the reading disability in PNH, particularly in the context of the numerous fMRI studies of dyslexic patients that have demonstrated alterations in the usual left hemisphere networks that appear to be responsible for reading (Shaywitz & Shaywitz, 2005).

6 Conclusions

In the end, a focus on the cognitive and functional consequences of disruptions in cerebral cortical development may allow insights from a relatively select group of patients with rare disorders to aid our understanding of, and approach to, the much larger population of children and adults with learning disabilities. In particular, data from more detailed behavioral studies of the reading problems faced by PNH patients may hold the promise of allowing us to refine our current models of reading development and reading breakdown. Ultimately, an increased appreciation of the neurobiological basis of reading disability, both in those with uncommon developmental brain disorders and more commonly in the wider population of dyslexics, will be one step toward the proper evaluation and remediation of children and adults with developmental disabilities.

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Neuroimaging Perspectives on Skilled and Impaired Reading and the Bilingual Experience

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Abstract Skilled, fluent reading involves mastery of multiple linguistic (e.g., phonological, semantic, morphological, syntactic) and related cognitive processes (e.g., processing speed, attention, working memory). Development of these processes is highly predictive of fluent reading. Among these, impairments in phonological processes such as phonological awareness and decoding (learning of spelling-to-sound correspondences) in combination with processing speed impairments are often implicated as the primary underlying deficits in developmental dyslexia. Here, we review relevant behavioral research on aspects of fluent reading development (phonology, semantics, processing speed) in skilled and disordered reading. We describe recent research in mapping the development of neural systems underlying these reading-related capacities, and their relevant gene-brain-behavior underpinnings. We consider the impact of cross-linguistic and/or multilingual experience on the development of the brain's reading circuitry. By incorporating behavioral, neural, and genetic research, across different populations (skilled and disordered reading, monolingual and multilingual reading), and across languages, these multiple sources

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of converging evidence inform the development of fluent reading and contribute to the goal of developing a comprehensive neurobiological model of reading.

Keywords Reading fluency • Neural systems • Gene-brain-behavior • Cross-language reading • Bilingual reading • Reading disorders • Phonology • fMRI • fNIRS • Neuroimaging

1 Introduction

Fluent reading is a product of skilled decoding and a complex process involving multiple underlying linguistic and cognitive components. The bulk of reading research, both on typical reading development and on disordered/delayed reading development, has primarily addressed phonological processing (including phonological awareness and phonological working memory) and naming speed (Arnell, Joanisse, Klein, Busseri, & Tannock, 2009; Swanson, Trainin, Necoechea, & Hammill, 2003). Children with developmental dyslexia can often be characterized by a discrete deficit in either phonological processing or processing speed, or a combination of both (McCardle, Scarborough, & Catts, 2001). Although phonology and processing speed appear to be most compromised in reading disabled cohorts, all aspects of language, including orthography, morphology, syntax and semantics are crucial for fluent reading. Aspects of cognition such as attention and memory are likewise crucial components of the development of skilled reading (Pugh et al., 2013). Early development of these capacities is linked to reading mastery and fluency in important ways. In this chapter, we describe our laboratory's recent research in mapping the neural systems underlying these reading-related capacities and our advances in developing a neurobiological model of reading. A neurobiological model of how multiple linguistic and cognitive systems give rise to reading crucially must look beyond monolingual English reading development in order to account for both universal and language-specific reading phenomena. An adequate model must consider cross-linguistic differences, as well as bilingual and multilingual experiences, and their impact on the development of the brain's reading circuitry. In our goal to develop a comprehensive model, we begin by reviewing relevant behavioral research on component processing in fluent reading, with specific focus on phonology, semantics, and naming speed. We then review current neurobiological findings relevant to gene-brain-behavior underpinnings of skilled and disabled reading in contrastive languages as well as monolingual versus bilingual populations, with an emphasis on neuroimaging research that permit such insights. We will finally conclude with further directions and new research questions in the cognitive neuroscience of reading.

2 Phonology

Understanding the role of phonology in reading is crucial if we hope to interpret the neural correlates of phonological processing in the brain's reading circuit. Phonology has received much attention in reading research because of its importance in the very early stages of learning to read. Children's awareness of and ability to manipulate the sound units in their native language, termed *phonological awareness*, is a strong predictor of later reading development (Bowey, Cain, & Ryan, 1992; Foy & Mann, 2006; Goswami & Bryant, 1990; Hatcher & Hulme, 1999; Hoien, Lundberg, Stanovich, & Bjaalid, 1995; Hulme et al., 2002, Hulme, Caravolas, Málkova, & Brigstocke, 2005; Melby-Lervåg, Lyster, & Hulme, 2012; Muter, Hulme, Snowling, & Taylor, 1997; Nation & Hulme, 1997; Nation & Snowling, 2004; Preston et al., 2010; Pugh et al., 2013; Wagner & Torgesen, 1987; Weber-Fox & Neville, 1999, 2001). A child's phonological awareness at the point in development when literacy is emerging (ages 4–6) predicts later literacy outcomes (Goswami & Bryant, 1990; Hulme et al., 2002; Wagner & Torgesen, 1987; Wagner et al., 1997; Ziegler & Goswami, 2005).

Good phonological awareness allows the subsequent understanding of the alphabetic principle in the beginning reader (Liberman, Shankweiler, & Liberman, 1989). Understanding that phonemes can correspond to letters is an important step for learning to read in alphabetic systems. The learning of spelling-to-sound correspondences allows the young reader to successfully decode an unfamiliar word by "sounding out" each letter (Share, 1995). When a child is faced with the task of recognizing a printed word, s/he can assemble a phonological representation by mapping from the orthographic units to their corresponding phonological forms, often referred to as the *phonological route*, (e.g., Frost, 1998). Indeed, there is evidence that all young readers access phonological representations in association with print for all languages (Georgiou, Torppa, Manolitsis, Lyytinen, & Parrila, 2012; Goswami, 2008; Panah & Padakannaya, 2008). With increased experience older, skilled, readers may come to rely to an increasing degree on direct associations between orthography and semantics (Share, 1995), the so-called *lexical route*. The phonological route remains relevant in reading frequent words as reading fluency develops. Indeed, there is evidence that phonological activation is both early and automatic in skilled reading (see Frost, 1998 for a review), and various experimental paradigms such as backward masking and priming, indicate that lexical access continues to be constrained by phonology (Lukatela & Turvey, 1994; Perfetti & Bell, 1991). In short, there is good evidence that phonology is still playing an important but more automated (faster) role – and importantly, if the phonological mapping is never mastered, reading will continue to be slow and labored (Frost, 1998; Pugh et al., 2013).

We must also consider differences among written languages. Languages vary in the degree to which spelling-to-sound mappings are multivalent; this has been referred to as orthographic depth (Frost, Katz, & Bentin, 1987). For example, languages such as Spanish, Italian and German have nearly one-to-one spelling-to-sound correspondences, termed consistent or *transparent orthographies* (Katz & Feldman, 1983). Many alphabetic languages have a transparent orthography, whereas English orthography is considered an *opaque orthography* with many inconsistencies in spelling-to-sound mappings (e.g., the letter ‘c’ can correspond to both the phoneme /s/ and /k/ as in ‘circus’). Irrespective of such cross-linguistic variation in orthographic depth, phonology is a key component of learning to read in both transparent and opaque orthographies (Caravolas, Lervag, Defior, Seidlova Malkova, & Hulme, 2013; Cossu, Shankweiler, Liberman, Katz, & Tola, 1988; Katz & Frost, 1992). Moreover, this general principle holds true across different writing systems, for example, alphabetic languages such as English and logographic languages such as Chinese (Lo, Hue, & Tsai, 2007; Wang, Yang, & Cheng, 2009).

A set of contemporary computational models of reading, known collectively as “triangle models of reading”, postulate that reading primarily consists of processes distributed over three levels of linguistic representation: orthography, phonology and semantics (Harm & Seidenberg, 2004). In order to decode a written word and access its corresponding meaning, orthographic networks activate corresponding phonologic and semantic networks. Skilled reading involves both the direct orthography-semantic connections as well as the orthography-phonology-semantics connections, and while the division of labour among these pathways changes over development all connections remain crucial to skilled word identification (Harm & Seidenberg, 1999, 2004).

There is considerable agreement that phonological processing deficits have a central role in reading impairments (Bradley & Bryant, 1983; Goswami, 2003; Goswami, Gerson, & Astruc, 2010; Landi, Mencl, Frost, Sandak, & Pugh, 2010; Lavidor, Johnston, & Snowling, 2006; Pugh et al., 2001; Torgesen, Wagner, & Rashotte, 1994; Wolf & Bowers, 1999). However, there is also evidence that children with reading impairments show deficits not limited to phonology (Ackerman & Dykman, 1993; Wolf & Bowers, 1999). Minimally, the processes contributing to successful reading include (1) attention to visual letters and visual processes involved in feature detection, and letter and letter-pattern identification, (2) the integration of this visual information with orthographic representations, (3) integration of orthographic representations with phonological representations, and (4) speed of activation of semantic and lexical information (Grainger & Holcomb, 2009; Seidenberg, Bruck, Fornarolo, & Backman, 1985; Wolf & Bowers, 1999). Theoretically, and practically, any of these component processes can contribute to reading impairments.

Thus, processes underlying rapid word recognition can show impairments that are not entirely reducible to phonological skills such as phonological awareness, indicating that indeed other aspects of language and cognition contribute to the development of reading. For instance, Wolf and Bowers (1999) offer a *double-deficit hypothesis* for reading impairment that implicates both phonological and naming speed as dissociable sources of reading difficulty. Here, phonological processing represents one side of the deficit, whereas naming speed represents another side.

3 Naming Speed

Although phonological processing deficits have received the lion's share of research focus in reading sciences, fast, automatic item retrieval and naming are also key components of skilled and fluent reading (Wolf & Bowers, 1999). Naming speed is not entirely dissociable from phonological processing because the phonological representation of a given word is continuously accessed during reading. In order for a child to successful read a printed word, s/he must recognize the target word and retrieve it from her lexicon to access meaning. Moreover, this process progressively becomes automated as a child progresses from a young beginning reader to an older more skilled reader. Skilled and fluent reading involves additional processing beyond the routinization of spelling-to-sound correspondence learning. Strong vocabulary knowledge is related to word reading mastery (Anderson & Freebody, 1983; Berends & Reitsma, 2006; Muter, Hulme, Snowling, & Stevenson, 2004; Oullette, 2006; Roth, Speece, & Cooper, 2002; Share & Leikin, 2004; Snow, Tabors, Nicholson, & Kurland, 1995). Familiarity with words may permit the child to access the lexical entry with greater weighting towards orthographic-to-semantic connections. Thus, semantic knowledge provides an important link between decoding a word and reading comprehension. For example, Berends and Reitsma (2006) observed that practice with printed words, with specific instructions focusing on the semantic characteristics of the word, promotes reading acquisition. Moreover, the size of a child's vocabulary is related to the ability to understand printed words (Anderson & Freebody, 1983; Proctor, August, Carlo, & Snow, 2006; Rolla San Francisco, Mo, Carlo, August, & Snow, 2006). The importance of semantic knowledge for skilled reading is well expressed by Perfetti and Hart (2002) and Perfetti (2007) in the Lexical Quality Hypothesis in which word knowledge is composed of multiple dimensions (phonology, orthography, semantics) and coherent representations of all these dimensions contribute to skilled reading.

As noted, retrieval speed can impact reading skill with measures such as Rapid Automatized Naming (RAN) shown to be a contributing factor to fluent word reading (Wolf & Bowers, 1999). Deficits in this capacity are characteristic of reading disability (Bowers & Swanson, 1991). Specifically, RAN tasks measure the speed and accuracy of naming an array of familiar stimuli such as digits, letters, or colors (Denckla & Rudel, 1974). Scores on such tests are consistently correlated with reading ability (Swanson et al., 2003). There is indication that RAN is at least partially dissociable from phonological ability. Indeed, RAN and phonological ability account for independent variance in reading achievement (Bowers & Swanson, 1991; Wolf et al., 2002). RAN scores significantly correlates with reading ability even when phonological awareness ability has been removed (Wolf et al., 2002). RAN is dependent on a wide range of cognitive skills as both speed and accuracy can be influenced by multiple different cognitive processes (Arnell et al., 2009). Certainly attentional processes strongly influence RAN performance, and indeed, children with attention deficit/hyperactivity disorder (ADHD) show reduced performance on RAN measures (Waber, Wolff, Forbes, & Weiler, 2000). RAN tasks require a participant to sustain focused attention over time and exhibit inhibition/suppression of previous and upcoming responses while the current response is planned or executed (Wolf & Bowers, 1999). These cognitive processes support fluent reading and have corresponding patterns of neural activation, which we discuss in detail below.

Decades of behavioral research have contributed a rich literature and an understanding of how aspects of linguistic knowledge (i.e. phonology, semantics) and developing cognitive abilities (i.e. rapid naming) contribute to successful reading acquisition. These components of the reading system are also candidates for reading disorders. Theories of reading disorders present deficits in single components (e.g. phonology) or combinations of these components (e.g. phonology and naming speed or working memory) as the underlying causes of reading disorders. Indeed, there is a strong body of scientific work that implicates various linguistic and cognitive skills in reading disorder.

However, behavioral results alone cannot fully reveal the extent to which typical reading acquisition is supported by each factor (phonological, semantic, cognitive, etc.,), the discrete versus overlapping contribution of each factor, and the static versus dynamic significance of each factor throughout the child's development. The use of functional neuroimaging technologies for developmental research of reading can adjudicate between these remaining considerations. For example, functional magnetic resonance imaging (fMRI) can reveal what brain regions support different aspects of reading, changes across development, and how these brain regions differ as a function of cross-linguistic variation, the child's experience (i.e. monolingual versus bilingual), or in atypical or delayed reading.

4 Reading and the Brain

Skilled reading involves mapping orthographic information onto phonological and semantic representations, the lion's share of which is performed by a reading network that can broadly be divided into three sub-systems: the ventral (occipitotemporal), dorsal (temporoparietal) and an anterior area centered around the left inferior frontal gyrus (LIFG). Visual word input is relayed to the left fusiform gyrus, occipito-temporal region also referred to as the "visual word form area"; VWFA, Brodmann's area (BA) 37 (McCandliss, Cohen, & Dehaene, 2003; Pugh, Mencl, Jenner, et al., 2000; Schlaggar & McCandliss, 2007). This region functions as a pre-semantic area and appears to be linguistically-tuned and largely dedicated to processing orthographic information (Sandak, Mencl, Frost, & Pugh, 2004). This functional specificity of the VWFA appears to be late developing and directly related to acquisition of literacy (Dehaene et al., 2010; Shaywitz et al., 2002). Developing reading ability is accompanied by a decreased response to faces in the left hemisphere's VWFA (Dehaene et al., 2010); rather the VWFA begins to respond to orthographic stimuli (Baker et al., 2007; Cohen et al., 2000; Shaywitz et al., 2002). Dehaene et al. (2010) contrasted neural response to spoken and written language, visual faces, and non-face, non-orthographic visual stimuli among adults with various levels of literacy. Neural responses to non-orthographic stimuli in the VWFA decreased with reading performance. This comparison of literate and illiterate adults revealed a significant decrease in neural response to face stimuli, but not to non-face/non-orthographic stimuli in the VWFA among literate versus illiterate adults. Reading acquisition may, to some degree, influence the lateralization of orthographic processing to the left hemisphere (VWFA) and face processing to homologous regions in the right hemisphere (FFA). The implication here is that experience of learning to read changes the brain and reveals to us the plasticity of the brain's reading circuitry.

Visual input to the VWFA extends into the ventral system including the middle and inferior temporal gyri (MTG, ITG) where word information appears to be semantically processed (Fiebach, Friederici, Muller, & von Cramon, 2002; Price, 2012). The dorsal temporoparietal system includes the inferior parietal lobule (IPL), with the angular gyrus, which is involved in lexical-semantic processing (Seghier, Fagan, & Price, 2010), and the supramarginal gyrus (BA 39 and 40), and has an important role in converting orthography into phonology (Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995; Moore & Price, 1999). The dorsal system also includes "classic" language architecture such as the superior temporal gyrus (STG, BA 21/22/42), which is known to be important in phonological processing (e.g., (Petitto et al., 2000; Zatorre & Belin, 2001).

The anterior reading system includes the left inferior frontal gyrus (LIFG), which includes pars triangularis, pars opercularis (Broca's area, BA 44/45) and pars orbitalis (BA 47), which is involved in syntax, morphology, semantics and phonology, including the search and retrieval of information about the meanings of words (Bookheimer, 2002; Caplan, 2001; Price, 2000, 2010, 2012; Sabb, Bilder, Chou, & Bookheimer, 2007). The more posterior portions of the LIFG show greater activation during tasks that involve sublexical phonological coding, phonological memory, and syntactic processing (Pugh, Mencl, Jenner et al., 2000). However, the more anterior portions of the LIFG show greater activation during tasks that involve semantic retrieval (Poldrack et al., 1999).

Regions within these systems, such as the supramarginal gyrus, LIFG, STG and VWFA, tend to activate for both words and pseudowords, but show greater activation for pseudowords versus familiar words (Bookheimer et al., 1995; Graves, Desai, Humphries, Seidenberg, & Binder, 2010; Heim et al., 2005; Shaywitz et al., 2002). When reading words, the left inferior, frontopolar, and dorsolateral prefrontal cortex (DLPFC) are recruited during the retrieval of semantic content of words. These areas show greater activation as compared with nonsense words, which show significantly less activation (Goldberg, Perfetti, Fiez, & Schneider, 2007). Words that have irregular or inconsistent mappings between spelling and sounds also show greater neural activation as compared with regularly-spelled words during oral naming (Fiebach et al., 2002; Fiez & Petersen, 1998). More, a word's semantic characteristics influence the phonological processing involved in word naming (Frost et al., 2005). Although naming is primarily driven by phonological assembly from the orthographic input, there is a trade-off between phonology and semantics, such that when phonological processing is slower and less accurate due to inconsistent spelling-to-sound mapping, semantics has a stronger impact on naming performance (Strain, Patterson, & Seidenberg, 1995, 2002). Neuroimaging studies have also demonstrated this tradeoff on activation with greater activation of the inferior frontal gyrus or the middle temporal and angular gyri, depending on the respective impact of phonology or semantics (Frost et al., 2005).

As children become skilled readers, several models suggest a relatively greater reliance on orthographic-to-semantic coding indicating that although phonological knowledge is important for reading, semantic knowledge becomes increasing important for later reading skill (Berends & Reitsma, 2006; Hoover & Gough, 1990; Snowling, 2004). For example, training in semantics for reading is only beneficial at later stages of reading, but not at early stages of reading (Berends & Reitsma, 2006). This relative shift from phonological to semantic weighting over the course of reading development has been argued to be associated with a shift in the recruitment of brain regions classically associated with aspects of language function (Jasińska & Petitto, 2013b; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). Jasińska and Petitto (2014) examined the development of neural systems for reading using functional Near Infrared Spectroscopy (fNIRS) in younger (ages 6–8) and older (ages 8–10) children using different word conditions that exploit differences in reading strategy. Children read regularly-spelled words with a one-to-one correspondence between letters and sounds (e.g., hill) and irregularly spelled words without a direct one-to-one correspondence (e.g., circus). Younger readers showed similar neural recruitment of the left STG for both irregular and regular words, however, older readers showed robust neural recruitment of the LIFG for irregular relative to regular words. The STG is known to be important in phonological processing, (e.g., Petitto et al., 2000; Zatorre & Belin, 2001) whereas the LIFG typically participates in syntax, morphology, semantics and phonology, including the search and retrieval of information about the meanings of words and is sensitive to the spelling-to-sound regularity/consistency) and frequency of words (Caplan, 2001; Fiez, Balota, Raichle, & Petersen, 1999; Foundas, Eure, Luevano, & Weinberger, 1998; Kovelman, Baker, & Petitto, 2008b; Price, 2010). Younger readers show greater neural activation in phonological processing tissue at an age when children rely heavily on phonology for reading (Jasińska & Petitto, 2014). The study therefore shows a focal brain correlate of a developmental reading milestone. Older readers also show activation in the STG that is consistent with their reliance on phonology during reading. However older readers also show greater neural activation in tissue classically associated with lexical access at an age when children begin to utilize larger grain sizes in processing words, including whole word units (Jasińska & Petitto, 2014). Moreover, this neural activation is greater for irregularly-spelled words, which have a greater reliance on the orthographic-to-semantic component versus the orthographic-to-phonological-to-semantic component.

Although much attention has been devoted to mapping the language and reading circuitry of the human brain, multiple additional regions of the brain support reading. Aspects of cognition such as working memory and attention are critical components of reading and are supported by regions in the frontal lobe such as the dorsolateral prefrontal cortex (DLPFC, BA 9/46) (Balconi, 2013; Petrides, 2005). Extensive neural maturation of the frontal lobes takes place between the ages of 3 and 6 years (Courchesne et al., 2000; Huttenlocher & Dabholkar, 1997; Lenneberg, 1967). Children begin formal reading instruction in school precisely at this age. Frontal cortex maturation, including the DLPFC, is particularly protracted as compared to other cortical regions (Cone, Burman, Bitan, Bolger, & Booth, 2008; Shaw et al., 2008). The left temporoparietal areas (STG, IPL), which represent key regions in the reading circuitry, mature earlier in comparison with frontal regions such as the LIFG, or the DLPFC (Cone et al., 2008; Shaw et al., 2008). The maturation of the frontal cortex and the cognitive skills that are supported by this brain region, in addition to other brain areas supporting language and reading, contribute to reading development (Monzalvo & Dehaene-Lambertz, 2013).

5 Reading Disability in the Brain

Behavioral studies have revealed differences in phonological awareness and RAN between children who are typical readers and children who show reading disabilities and/or delays (RD). There are corresponding functional differences between typical and atypical readers. A number of functional neuroimaging studies demonstrate disruptions to the left hemisphere posterior reading circuitry including both dorsal and ventral systems. There is a relative under-activation of these neural systems while children with reading impairments are processing print stimuli, including both words and pseudowords (Brunswick, McCrory, Price, Frith, & Frith, 1999; Paulesu et al., 2001; Pugh, Mencl, Jenner et al., 2000, Pugh et al., 2001, 2013; Salmelin, Service, Kiesila, Uutela, & Salonen, 1996; Shaywitz et al., 1996, 1998, 2002). A key distinction between typical readers and children with reading impairment is not limited to differential activation of brain regions that comprise the reading circuit. Rather, the connections between the different sub-components of the reading circuitry vary in typical and impaired reading. The entire reading system must function cooperatively to give rise to accurate and fluent reading. For example, children who show reading impairments show weaker correlations between the angular gyrus and other sites involved in reading as compared with typical readers (Horwitz, Rumsey, & Donohue, 1998; Pugh, Mencl, Shaywitz et al., 2000). This diminished connectivity appears to be related with diminished ability to assemble phonological units from orthographic form or perhaps to integrate this information with semantic knowledge.

As a compensatory mechanism to the hypo-activation of the left hemisphere reading circuitry, children with reading impairments show greater activation of the right hemisphere while reading. The disruptions to the left hemisphere circuitry and corresponding additional right hemisphere activation has been observed across languages that vary in orthographic depth and writing systems, including Finnish, German, French, Italian and Chinese (Paulesu et al., 2001; Salmelin et al., 1996; Shaywitz et al., 2002; Siok, Perfetti, Jin, & Tan, 2004). Such cross-linguistic research indicates that reading impairments arise in global phonological processes underlying orthography-to-phonology mapping common to all languages. When this capacity breaks down in reading impairment, there is often additional recruitment of right hemisphere brain regions that support compensatory processing particularly when task demands are high. There is evidence that children with reading impairment show greater engagement of prefrontal dorsolateral sites as compared with typical readers (Brunswick et al., 1999; Salmelin et al., 1996). Children with reading impairments may be showing an overreliance on covert pronunciation (articulatory recoding) in recruiting frontal regions to compensate for poor phonological decoding (Frost et al., 2008). Additional right hemisphere activation may reflect increased visual processing of the orthographic form in lieu of adequate phonological processing, or more generally, may reflect increased effort during reading that requires additional brain regions for support.

Compared with typical readers, children with reading disabilities show reduced grey matter volume in several brain regions including left occipitotemporal and temporoparietal areas, the fusiform gyrus as well as the cerebellum (Hoeft et al., 2007; Kronbichler et al., 2008; Raschle, Chang, & Gaab, 2011). Grey matter volume in these brain regions is positively related with pre-reading and reading skills, including phonological processing and rapid automatized naming (Kronbichler et al., 2008; Pernet, Andersson, Paulesu, & Demonet, 2009). White matter differences are also observed between typical readers and children with reading disabilities (Klingberg et al., 2000; Silani et al., 2005; Steinbrink et al., 2008). White matter organization appears weaker (via diffusion tensor imaging; DTI) in LIFG, left temporoparietal and posterior reading areas (Klingberg et al., 2000; Rimrodt, Peterson, Denckla, Kaufmann, & Cutting, 2010). Atypical functional activation for reading among children with reading disabilities may be associated with structural brain differences (Clark et al., 2014; Hoeft et al., 2007).

The functional and structural brain characteristics of children with reading disabilities in comparison to children with typical reading skills are well characterized, with an increasing number of studies converging on the neural basis of skilled and impaired reading. More recently we have begun to examine neurochemistry in the typical versus atypical reading brain (Pugh et al., 2014). We sampled individual differences in neurochemistry in children early in reading development (age 7) using magnetic resonance spectroscopy (MRS). Concentrations of choline and glutamate neurometabolites measured at a midline occipital region the brain were negatively correlated with reading skills and measures of phonology and vocabulary. The structural white matter anomalies that are widely observed in children with reading disabilities may be related to choline and glutamate levels in the brain. Moreover, elevated glutamate levels in the brain may also be related to hyperexcitability and consequently affect the coherence of neural networks that support learning to read. The role of neurometabolites in the formation of a stable reading circuitry is just beginning to be investigated, but points to new research directions in reading disability, and the possibility of neuropharmacological treatments. Thus a growing body of evidence reveals structural, functional, and neurochemical signatures for RD. With clear indications that RD is heritable (Castles, Bates, Coltheart, Luciano,

& Martin, 2006; Dennis et al., 2009; Fisher & Francks, 2006; Grigorenko, 2001, 2007; Landi et al., 2013), work across these levels of analysis will yield better neurophenotypes and better causal accounts going forward.

Although one objective has been to establish the brain bases of skilled and impaired reading, the major question that still remains is, of course, one concerning the neural plasticity of these brain bases. Are the neural differences between skilled and impaired readers modifiable with good evidence-based treatments? Are these circuits fundamentally disrupted or just poorly organized? Treatments for reading disorders (once a diagnosis has been confirmed) typically take place in schools or special education intervention programs and can result in reading gain depending on the type, intensity and length of treatment (Gabrieli, 2009). If the intervention is more intensive (daily instruction and practice for weeks or months, for example), occurs in smaller groups (e.g. one-to-one teacher-student ratio), incorporates phonological decoding and awareness training, and is begun earlier in younger children, then gains in reading fluency may be seen by ~50 % of students for years after returning to the regular curriculum (Gabrieli, 2009). Treatment for reading disorders result in functional changes in the brain's activation patterns, resulting in increased activation in classic left hemisphere temporoparietal reading networks and some reductions in frontal areas that typically show hyperactivation in reading disorders (Aylward et al., 2003; Eden et al., 2004; Gabrieli, 2009; Temple et al., 2003).

6 Reading Across Languages

The functional neural anatomy underlying reading has been studied across a variety of languages, both alphabetic and non-alphabetic (Chee, O'Craven, Bergida, Rosen, & Savoy, 1999; Fiebach et al., 2002; Jasińska & Petitto, 2014; Kuo et al., 2004; Paulesu et al., 2000; Salmelin et al., 1996). Neuroimaging studies have revealed activation in left hemisphere brain regions (occipitotemporal, temporoparietal, and inferior frontal networks) while reading in English (e.g., Pugh, Sandak, Frost, Moore, & Mencl, 2005), which are also activated while reading in other languages. For example, brain regions that are involved in phonological processing in English are also active in Chinese in tasks such as homophone judgment (Kuo et al., 2004). Thus, it appears at a global level, varied language and writing system recruit the same brain regions for reading. However, language differences in the orthography-phonology relationship that is crucial at the onset of literacy, as well as other aspects of language structure (for example, morphologically-rich, highly inflected languages with lax word order such as Russian versus analytical languages with stricter word order such as English) have been shown to produce some differences in the degree and extent of activation, with limited differences in location. For example, Kovelman, Baker, and Petitto (2008a) observed difference in neural activation of the LIFG for English sentences varying in syntactic complexity, but not for Spanish sentences. The precise manipulation that resulted in different neural activation in the English contrast, but not the Spanish contrast was depended on differences in the relevance of word order versus morphological inflection between the two languages: English favoring word order, and Spanish favoring inflectional morphology (Kovelman et al. 2008a). Irrespective of these language-specific differences, any comprehensive models of reading should incorporate the cognitive and linguistic processes common to all languages as a set of *reading universals* (Frost, 2012).

The conception of reading universals posits that disorders in reading should be similarly realized across languages. Differences in the contribution of phonological or semantic processing to reading disorders may exist across languages that differ with respect to these aspects of linguistic knowledge. However, an overall consistent pattern of deficits in phonology, semantics, RAN and other cognitive capacities emerges in cross-linguistic comparisons of reading disorders, with finer features of the reading disorder exhibiting sensitivities to language specifics (Pugh, 2006). Evidence for universals in reading disorders comes from studies of languages that differ in their orthographic-to-phonological mapping (transparent versus opaque orthographies), and therefore are theoretical candidates for revealing reading disorders that vary with orthographic depth. Ziegler, Perry, Ma-Wyatt, Ladner, and Schulte-Korne (2003) compared reading disorder in German (regular orthographic-to-phonological mapping) and English (irregular orthographic-to-phonological mapping), yet their results clearly showed the similarities between children with reading disorders were far greater than their differences across these two languages (Ziegler et al., 2003). Reading disorders across languages manifest as a failures to develop the functional specialization of the VWFA (Paulesu et al., 2001; Shaywitz et al., 2002). Beyond behavioral and neural similarities in reading disorders across languages, the heritability of reading disorder is strong evidence that there is an underlying biological contribution to reading disorder, which is not (and ought not) to be sensitive to cross-linguistic variation (Grigorenko, 2001).

7 Reading in the Bilingual Brain

How do a bilingual child's two languages impact the brain's neural circuitry for reading? Though much more is now known about the process by which the *monolingual* brain reads (Frost et al., 2009; McCandliss et al., 2003), the process by which the *bilingual* brain reads in each of their two languages remains comparatively less understood (Berens, Kovelman, & Petitto, 2013; Jasińska & Petitto, 2013b, 2014; Kovelman et al. 2008a, 2008b; Lafrance & Gottardo, 2005; Lesaux & Siegel, 2003; Lipka & Siegel, 2007). The bilingual brain must be able to process orthographic, phonological and semantic information across two languages while reading. Moreover, the relationship between orthography, phonology and semantics in each of a bilingual's two languages can vary, further complicating reading in two languages.

Early life bilingual exposure is associated with a bilingual phonological processing advantage (Bialystok, Majumder, & Martin, 2003; Kovelman et al. 2008a;

Petitto & Holowka, 2002; Petitto et al., 2012). Bilingual infants demonstrate greater and longer neural sensitivity to universal phonetic distinctions when monolingual infants can no longer make such discriminations. Early bilingual exposure may provide a linguistic "Perceptual Wedge" that extends infants' sensitivity to universal phonetic contrast and may later aid language and reading development in childhood (Jasińska & Petitto, 2011; Petitto et al., 2012). Indeed, bilingual school-aged children outperform their monolingual peers on measures of phonological awareness (Bialystok et al., 2003; Bruck & Genesee, 1995; Eviatar & Ibrahim, 2000; Jasińska & Petitto, 2014; Kovelman et al. 2008a; Petitto et al., 2001, 2012; Rubin & Turner, 1989). Children educated in bilingual English-Spanish schools from monolingual English-speaking homes outperform children educated in monolingual English schools on a complex phonological awareness task requiring children to break apart a word into individual phonemes (Kovelman et al. 2008a). Bilingual children exposed to two languages from birth show better performance on measures of phonological awareness (phoneme deletion and phoneme segmentation tasks) and word reading tasks when compared with their monolingual peers (Jasińska & Petitto, 2013a). Moreover, English monolingual children who had been exposed to their new language for the first time when they entered a French language program in school also showed higher performance on measures of phonological awareness and word reading in English relative to their monolingual peers who were attending monolingual English schools (Jasińska & Petitto, 2013a, Revise and Resubmit) . Collectively, these studies provide compelling evidence that bilinguals can have a linguistic – specifically phonological, and reading advantage. As an aside, there are still some inconsistencies in the literature specifically concerning differences in vocabulary size between monolingual and bilingual children. Differences emerge between monolinguals' vocabulary size when compared with bilinguals' vocabulary size in only *one* of their two languages, which can be misleadingly interpreted as a bilingual disadvantage. Yet, similarities are found when monolinguals' vocabulary size is compared with bilinguals' vocabulary size in *both* of their two languages (Petitto & Holowka, 2002; Poulin-Dubois, Bialystok, Blaye, Polonia, & Yott, 2013).

A growing body of research shows that bilingual experience in early life has the potential to yield changes in the patterns of neural activation in these language and reading related neural regions. Using fMRI, differential recruitment of language-related brain regions such as the LIFG has been previously observed for bilingual adults as compared with monolingual adults while reading sentences (Kovelman et al. 2008b). Bilingual adults were found to recruit a greater extent and variability of the LIFG while completing a syntactic sentence judgment task relative to monolinguals. The greater recruitment of neural resources supporting language processing in the bilingual brain showed that early exposure to two languages modifies the neural activation of networks that underlie language processing, and reveals the brain's "neural signature" of bilingualism (Kovelman et al. 2008b). This "neural signature" is also found in the developing brain, indicating that early bilingual exposure can modify language-related brain regions before they have fully matured. Using fNIRS neuroimaging, both bilingual children and adults were found to show greater neural activation in classic language brain areas, including the bilateral superior temporal gyrus and the inferior frontal gyrus during a sentence reading task (Jasińska & Petitto, 2013b) and a word reading task (Jasińska & Petitto, 2014). More recently, we have observed greater functional connectivity between left and right hemisphere language areas in bilingual children as compared to monolingual children while reading (Jasinska & Petitto, submitted). Bilingualism may provide enrichment for the developing brain realized as greater connectivity. That bilingual readers show a greater extent and variability of neural activation in classic language (LIFG, STG, IPL) areas as well as their right hemisphere homologues and higher cognitive (DLPFC, RLPFC) brain areas and increased functional connectivity suggests that bilingualism may lead to enhanced linguistic and cognitive processing and reveals the extent of neural architecture underlying language and reading that can be modified through early life language experience.

Research on the neural basis of healthy and typical bilingual language and reading development continues to amass evidence of a bilingual "neural signature", that is, a greater extent and variability in the patterns of neural activation that support language and reading in the bilingual brain (Jasińska & Petitto, 2013b, 2014; Kovelman et al. 2008b, Kovelman, Shalinsky, Berens, & Petitto, 2008; Petitto et al., 2012). Bilingual exposure also has the potential to yield structural changes in the brain (Mechelli et al., 2004). These structural and functional neural changes occur as a function of early life bilingual experience; moreover, such neural changes are at least partially modulated by the age of bilingual exposure (Jasińska & Petitto, 2013b).

Yet, we have virtually no knowledge of whether bilingual exposure affects reading disorders, and if so, how? Would reading disorders present in one or both of a bilingual's two languages? If the reading disorder does present in both languages, would language-specific differences emerge? These questions remain unanswered; yet pursing this line of research has the potential to reveal new information about reading disorders in a bilingual population. Indeed, the majority of the world speaks multiple languages, and thus the focus on reading disorders in predominantly English-speaking monolinguals is under representative of the full scope of reading disorders.

One exciting hypothesis for reading disorders emerges from research on bilingual language and reading processing. Bilinguals show distinctive neural activation changes in phonological processing, which are apparent even in the young bilingual infant (Petitto et al., 2012; Werker, 2012). This pattern of neural activation in the young bilingual infant may underlie the phonological advantages for reading in school-aged bilingual children (Berens et al., 2013; Bialystok et al., 2003; Jasińska & Petitto, Revise and Resubmit; Kang, 2010; Kovelman et al. 2008a; Kuo & Anderson, 2012; Laurent & Martinot, 2009a, 2009b). Given the widely observed phonological processing deficits in reading disorders, it begs us to consider if bilingual advantages in phonological processing can ameliorate some of these deficits in reading disorders.

The hypothesis that early life bilingual exposure may provide an advantage for reading disorders through enhanced phonological processing is not without merit.

Phonologically-based interventions for reading disorder show promising results: children show gains in reading fluency after undergoing a year-long treatment where training and practice in mapping letters to sounds was the focus (Shaywitz et al., 2004). A child who grows up bilingual has two phonological systems, and has greater experience with phonology. The possibility that reading disorders may present less frequently in children who grow up bilingual from birth *because* of growing up bilingual needs to be formally investigated.

8 Future Directions

Research from our laboratory as well as others converge on a similar set of findings regarding the neural circuitry that gives rise to skilled, fluent reading. Skilled reading involves mapping orthographic information onto phonological and semantic representations, which is performed by left-hemisphere frontal, temporoparietal and occipitotemporal cortical regions. The growing set of scientific findings implicates these brain regions, specifically the supramarginal gyrus, the posterior interior frontal gyrus, the superior temporal gyrus, and the VWFA, in aspects of phonological processing. This suggests that these brain regions are phonologically "tuned" and support this key aspect of reading. This is particularly relevant given that a child's phonological awareness at times in development when literacy is emerging is predictive of later literacy outcomes. By contrast, the angular gyrus, the inferior and middle temporal gyri, the anterior inferior frontal gyrus and the dorsolateral prefrontal cortex have more of a role in abstract lexico-semantic function.

However, there are variations in this system in instances where a child's reading skill is delayed and/or disordered. Reading impairment in the brain is marked by consistent neural observations including hypo-activation of the left hemisphere posterior reading circuitry, decreased connectivity between sub-systems of the reading circuit, and additional (compensatory) recruitment of the prefrontal cortex and right hemisphere regions. Specifically, disruptions to the reading circuitry that are characteristic of delayed/disordered reading often correspond to behavioral deficits in phonological processing and decoding. Treatments focusing on phonology have resulted in improvements to reading fluency, and are accompanied by increased activation in left hemisphere posterior reading areas (Eden et al., 2004; Gabrieli, 2009; Shaywitz et al., 2004). More, new directions in neuropharmacological treatment for reading disorder are now being investigated given recent exciting findings from Haskins Laboratories indicating neurometabolites such as glutamate and choline are involved in the development of the brain's reading circuitry (Pugh et al., 2014).

The majority of research on the reading brain has predominantly focused on a monolingual English-speaking population, however, there are also variations in the brain's reading circuitry that arise as a consequence of early-life dual-language experience and yield reading advantages. The young, healthy and typical *bilingual* reader shows greater neural recruitment of brain regions classically associated with language function and reading as well as corresponding regions in the right hemisphere. Early exposure to two languages modifies the neural activation of networks that underlie language, and in turn, reading.

Establishing the neural circuitry of reading in the (predominately) English monolingual brain has yielded highly valuable information that has allowed us to track healthy development and compare this against delayed and/or disordered development. Crucially, this information serves as the foundation to developing targeted intervention for reading. Yet, the majority of the world's children are growing up bilingual. Therefore, the task ahead is to refine the typical neuro-maturational timetable for the bilingual neural circuit and understand how it differs from bilingual reading impairments. We must also consider the possibility that early bilingualism may ameliorate, or even partially prevent, reading disorders. We offer a novel and bold hypothesis that the rich early-life phonological experience that a bilingual child has as compared to her monolingual peer may promote healthy and typical reading development.

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1. Jasińska, K. & Petitto, L.A. (2014). Development of Neural Systems for Reading in the Monolingual and Bilingual Brain: New Insights from functional Near Infrared Spectroscopy Neuroimaging. *Developmental Neuropsychology. 39(6*), 421–39. doi: 10.1080/87565641.2014.939180

2. Jasińska, K. & Petitto, L.A. (*Revise and Resubmit*). Age of Bilingual Exposure Predicts Distinct Contributions of Phonology and Semantics to Successful Reading Development. Manuscript submitted for publication.

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The Role of Executive Functions in the Reading Process

Tzipi Horowitz-Kraus

Abstract “Executive functions” (EF) is an umbrella term for a set of cognitive abilities that are thought to be controlled by the frontal lobe of the brain. The development of these abilities relies on the use of different language skills, including reading. Dyslexia is a specific case of reading impairment that is primarily a result of phonological deficit. In this chapter, the involvement of EF during reading and the possible contribution of executive dysfunction to dyslexia are described. The effect of an executive-based (speed of processing, working memory and visual attention) reading intervention that can improve reading ability in both children and adults with dyslexia by re-wiring brain regions important for both reading and executive functioning is also reviewed. The role of EF in reading may have future implications for diagnosing dyslexia and improving intervention therapy for individuals with reading disabilities.

Keywords Dyslexia • Executive functions • Error detection • Fluency • Training

1 Executive Functions

What Are Executive Functions?

Executive functions (EF) are mental processes that are thought to originate from the prefrontal cortex (PFC) and are used in planning, organizing, learning, etc. (Horowitz-Kraus, Holland & Freund, 2016). These abilities are used to manage attention, emotion, and behavior in relation to determination to reach goals (Horowitz-Kraus, Holland et al., 2016). More specifically, some key EF are

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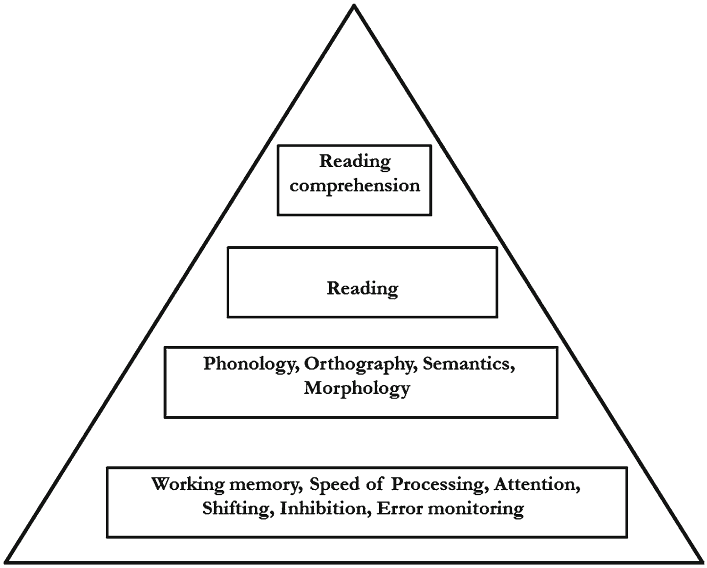

Fig. 1 The reliance of reading and reading comprehension on executive functions

planning, *initiation*, *working memory*, *self-control* (*inhibition and monitoring of performance*), *speed of processing*, *attention*, and *task switching* (Zelazo, 2010) (see also Fig. 1). *Planning* involves goal-directed management techniques that are crucial for task performance; what is the goal, how am I going to pursue it, do I have the right tools and if not, what do I have to do in order to get them? (Zelaso et al., 2003). When there is a plan in place, then the individual can initiate it. *Initiation* is the ability to start a task in a timely manner, while keeping in memory the necessary details for task performance using working memory. *Working memory* is defined as the ability to hold and manipulate several items in memory (Booth, Boyle, & Kelly, 2014). *Self-control/monitoring* is the ability to monitor performance and learn from mistakes, which is done by comparing the desired with the actual response (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000). *Self-control/inhibition* is preventing the execution of a particular, non-relevant behavior (Booth et al., 2014). *Speed of processing* is the time elapsed between when a subject perceives a stimulus until the moment the response is executed (Miller & Vernon, 1997). *Attention* is orienting to stimuli in the visual/auditory space (Posner, Snyder, & Davidson, 1980) and *switching* is the ability to change attention focus from one activity/modality to another (Kieffer, Vukovic, & Berry, 2013). All of these functions are necessary for learning, and individuals who have impaired EF are neither capable of self-regulating their behavior nor retaining knowledge as well as those with functional EF (Booth et al., 2014).

The development of EF is essential for intact personal relationships, as well as for academic success (Zelazo et al., 2003). A developing child uses these abilities to learn how to communicate by focusing the auditory attention to words, matching them to a semantic meaning, and holding them in working memory (Booth et al., 2014) to then be able to comprehend narratives (Horowitz-Kraus, Vannest, & Holland, 2013). Learning a new cognitive task or activity and applying it rely on processing visual or auditory stimuli and repeating them in a fast processing manner while inhibiting unnecessary stimuli, until the behavior becomes automatic and effortless (Kraus & Horowitz-Kraus, 2015). These abilities are supported by the maturation of the prefrontal lobes and specifically of the PFC (Horowitz-Kraus, Holland et al., 2016).

Developing in infancy, the maturation of the PFC peaks at around 25 years of age (Giedd, et al., 2009). Corresponding to frontal lobe maturation, initially EF develop rapidly in childhood and then gradually slow during early adulthood (Kieffer et al., 2013). It is therefore not surprising that different cognitive tasks that rely on EF are challenging for children, especially when entering school at the age of 6 (Horowitz-Kraus, Holland et al., 2016). A specific example of a higher-order ability that relies on EF that a young child needs to cope with is reading.

Reading and Executive Functions

Reading is defined as the ability to translate written graphemes into corresponding sounds in a fluent and efficient manner (Breznitz, 2006) and relies on several basic linguistic abilities, such as phonology, semantics and orthography. Phonological ability involves the relationship between abstract graphemes and their corresponding sounds. Semantics represents the meaning of a particular word, which directly affects reading comprehension (Horowitz-Kraus, Grainger, DiFrancesco, & Holland, 2014). In addition to these basic linguistic abilities, reading involves an orthographic component that enables the recognition of words and word-parts in a holistic manner. A well-defined model of reading called the Parallel-processing model, describes the synchronization between these three key components in reading ability (Seidenberg & McClelland, 1989). This model demonstrates how word reading requires decoding that involves perception of the word in the visual modality and recoding of its sounds in the auditory phonological system, followed by evoking the semantic representation of the word from the mental lexicon (Breznitz, 2006; Seidenberg & McClelland, 1989). During the reading acquisition period, the young reader relies more heavily on the ability to translate the letters into corresponding sounds and to a lesser extent relies on the orthographic route to derive a meaningful representation of a given word. With time, the young reader starts developing a wider mental lexicon with a "bank" of words that can be read holistically using the orthographic processor, and reliance on phonology becomes of limited use only for unfamiliar or long words. Given the description of this process, which involves focused attention, retrieval, fast speed of processing to enable the semantic integration, and also working memory to manipulate the sounds within a word, it seems reasonable that the reading process relies heavily on EF

(Horowitz-Kraus, Holland et al., 2016) (see Fig. 1 for the different EF involved in the reading process).

The primary EF that reading relies on are *inhibition*, *working memory*, *speed of processing*, *attention switching* and *self-control* (Booth et al., 2014). Working memory is required both at the letter level (for unfamiliar letter-by-letter decoded words) as well as at the sentence level (remembering what was read earlier) (Kieffer et al., 2013). The role of working memory in technical reading is to hold sound representations during the decoding phase, until merging all the sounds for a coherent word and then matching for meaning. Inhibition also plays an important role in reading. For example, the ability to inhibit the eye-gaze from moving to the next word before the earlier word was fully decided or alternatively, to inhibit moving to the next line before complete reading of the current one (Booth et al., 2014). Visual attention is necessary for the performance of every reading task, since the eyes should follow the graphemes and the lines in order (Vogel, Petersen, & Schlaggar, 2014). The involvement of switching in the reading process is by the demand of smooth shifting between one line to the other or even by means of switching between decoding and holistic word recognition at the word level. Reading requires a fast speed of processing to quickly synchronize the auditory (sounds) and the visual (words/letters) in the text (Breznitz & Misra, 2003). If the speed is too slow, then the load on working memory and the attempt to keep track via synchronizing is too heavy, which may impair semantic and comprehension processes (Breznitz & Misra, 2003). Other evidence for the reliance of reading on speed of processing and automatic and fast retrieval of information has been demonstrated by a recent neuroimaging study that used the verb-generation task (Horowitz-Kraus et al., 2013). The researchers determined that proficient word reading by 17-year-old adolescents was correlated with EF-related brain regions [Brodmann areas (BA) 10, 9] as well as with a reading-related region (BA 37) while performing an oral verb-generation task (i.e., a fluency task). This study demonstrated that better reading performance was correlated with a gradual increase in left-lateralized activation of reading and EF regions from the ages of 6–11 to 17, which connects reading to a fast and automatic retrieval of verbs. The commander of all of these processes is *self-control* (performance monitoring), mainly through the error-monitoring process. The error-monitoring system is a cognitive mechanism that is thought to emerge from the anterior cingulate cortex (ACC; BA 24) in the anterior portion of the frontal lobe, which shares strong anatomical and functional connections to the PFC by sending and receiving neural transmissions to the PFC (Scheffers & Coles, 2000). This cognitive process underlies the learning mechanism in general and is a basis for reading in particular (Horowitz-Kraus & Breznitz, 2008). The main role of error monitoring in the reading process is the recognition of reading errors and prevention of error repetition (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991). When a reader makes a reading error, the error-monitoring system regulates comparison of the actual and desired responses (i.e., the actual word that was read is compared with the stored mental representation of that word in the mental lexicon). In case of an erroneous response, a mismatch occurs and a negative event-related potential (ERP) called error-related negativity (ERN) is evoked within approximately 100 ms of execution of the erroneous response and can be distributed to frontal-lobe electrodes (Falkenstein et al., 1991). Interestingly, another negative potential called correct-related negativity (CRN) also is evoked in the same time frame and in the same scalp distribution as ERN and represents a correct response, resulted from conflict and uncertainty (Pailing & Segalowitz, 2004). In healthy individuals, CRN is smaller in size than ERN (Pailing & Segalowitz, 2004).

Dyslexia and Executive Functioning

Dyslexia is a specific impairment in reading that cannot be attributed to other neurological deficits and is defined by slow and/or inaccurate reading that continues into adulthood despite remedial intervention and repeated exposure to the written language (IDA, 2011). There is cumulative data suggesting that both children and adults with dyslexia also share a deficit in executive functioning.

Previous studies have identified deficits in a sub-domain of executive functioning in both children and adults with dyslexia (Altemeier, Abbott, & Berninger, 2008; Brosnan, Demetre, Hamill, Robson Shepherd et al., 2002; Helland & Asbjornsen, 2000; Horowitz-Kraus, 2014; Gooch, Snowling, & Hulme, 2011; Kraus & Horowitz-Kraus, 2015; Menghini, Carlesimo, Marotta, Finzi, & Vicari, 2010, Reiter, Tucha, & Lange, 2005; Tiffin-Richards, Hasselhorn, Woerner, Rothenberger, & Banaschewski, 2008). One of the only ERP studies to examine the impairment of EF in individuals with dyslexia (Horowitz-Kraus, 2014) used the Wisconsin card-sorting task, which is a task that encompasses several EF domains. For this task, participants are presented with 64 cards with a different combination of shapes (triangles, circles, and squares), colors (red, blue, green, and yellow) and numbers (1–4). One key card is presented, and participants are asked to match this card with one of four presented cards. Following each response, the participant is provided with an auditory feedback as to whether the response was correct (and therefore the participant should continue choosing this response) or erroneous (and therefore the participant has to choose another rule to match the target card with another of the other four presented cards). This test often is used to determine executive functioning abilities since it involves both switching and working memory (Nyhus & Barcelo, 2009). Twelve-year old children with dyslexia demonstrated smaller ERP components when processing the cards presented and when required to change the rules, compared to age-matched typical readers (Horowitz-Kraus, 2014). Since these components represent early attention abilities (i.e., N100) and speed of processing (i.e., P300), it was postulated that the difficulties in EF impaired the children's ability to reach the same accuracy scores in the Wisconsin task as age-matched typical readers. It also was suggested that impaired working memory prevents children with reading difficulties to reach the accuracy scores of typical readers in the Wisconsin task, as this task involves the maintenance of the correct rule in memory. This working memory deficit may be linked to an impairment in phonological processing that directly impairs reading (Horowitz-Kraus, 2014), which is compatible with a theory previously postulated for the relationship between working memory and phonological processing (Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986). Difficulty in working memory may also result in impairment of the ability to comprehend written materials, resulting from an attempt to decode words that overloads the working memory processor since all the sounds are needed to be installed until a meaningful word is reached. This may create a bottle-neck that impairs the ability to comprehend longer sentences (Breznitz & Share, 1992; Horowitz-Kraus & Breznitz, 2011).

Adults with dyslexia have also been reported to have difficulty when performing the Sternberg task (Horowitz-Kraus & Breznitz, 2009). In this task, participants are requested to look at and memorize a list of digits. Then a probe digit is presented and the participant has to decide whether or not that item was actually in the list (Sternberg, 1966). Difficulty performing this task was associated with the participants' reading impairment (lower number of words per minute was positively correlated with lower scores in the memory task) as well as with smaller ERP components related to error monitoring (i.e., ERN). The impairment in working memory, in particular slower speed of processing and error-monitoring deficit, may result in lower outcomes in this task (Horowitz-Kraus & Breznitz, 2009).

Individuals with dyslexia have impaired inhibition skills, and it has been suggested that their difficulties in mapping graphemes to phonemes is related, among others tasks, to difficulties in inhibition (Booth, Boyle et al. 2014). Speed of processing is essential for fast and automatic reading, since the time that elapses between perceiving the orthographic representation (letter or word) and matching its phonological representation (sounding it out) should be fast and the process should be effortless (i.e. automatic) (Breznitz & Misra, 2003). If the speed of matching these components is slow, then the overload on working memory becomes greater, which results in inefficient and slower reading that in turn, can lead to deficits in comprehension (Breznitz & Misra 2003; Breznitz & Share, 1992). It has been documented that both children and adults with dyslexia demonstrate a slow speed of processing (Breznitz, 2006; Breznitz & Misra, 2003; Horowitz-Kraus & Breznitz, 2011). Recently, it has been shown that a slow speed of processing, measured using the nonverbal (from the WAIS (Wechsler, 1999) and verbal speed of processing (Rapid Automatized Naming, after (Denckla & Rudel, 1976) tests, results in slower reading speed in adults with dyslexia when reading both individual words and sentences (Horowitz-Kraus & Breznitz, 2011). It also has been suggested that a slow speed of processing is related to additional cognitive impairment found among dyslexic readers, which is an impaired error-monitoring ability (Horowitz-Kraus & Breznitz, 2008).

Dyslexia and Error Monitoring

Both children and adults with dyslexia have impaired error monitoring during the reading process that is manifested by smaller ERN than typical readers during reading errors (Horowitz-Kraus & Breznitz, 2008, 2011, 2013). These differences in error monitoring may be explained based on the 'self-teaching' theory. The self-teaching theory was introduced in the mid 1990s by Share who suggested that a word template becomes part of beginning readers' mental lexicon, after several successful exposures to that word template (Share, 1995). However, this may not be the case for dyslexic readers who make different errors for the same word each time they encounter it. Since there is not a constant error pattern for reading mistakes and the templates are not being installed, the construction of a stable mental lexicon is prevented (Horowitz-Kraus & Breznitz, 2008). Therefore, the smaller ERN in individuals with dyslexia may be the result of this impaired mental lexicon in that if there is no stored "correct" representation of the written word, then a comparison of the actual erroneous word and the unstable stored one results in a smaller ERN (Horowitz-Kraus & Breznitz, 2008).

Dyslexics have smaller gaps between ERN and CRN amplitudes when reading, which results in a similar brain response to both correct and erroneous reading compared to typical readers (ERN/CRN gap equals ~5 μV for typical readers and ~1.5 μV for dyslexic readers; see Horowitz-Kraus & Breznitz, 2008). A larger ERN/CRN gap represents a greater distinction between correct reading and erroneous reading that should be modified in the future. Both children and adults with dyslexia have smaller ERN/CRN gaps during reading due to having a relatively smaller ERN for reading errors (based on not having "correct representation" of the word) and a relatively larger CRN as a result of a conflict and uncertainty during reading (Horowitz-Kraus & Breznitz, 2011). In other words, it seems that with respect to error monitoring, erroneous and correct reading patterns are perceived the same by dyslexics, which may provide a physiological explanation for the repetitive erroneous reading behavior in dyslexic reading. Due to the consistency of these results across ages [children: (Horowitz-Kraus & Breznitz, 2013); adults: (Horowitz-Kraus & Breznitz, 2008)] and orthographies [Hebrew: (Horowitz-Kraus & Breznitz, 2008, 2011, 2013); English: (Horowitz-Kraus & Breznitz, 2013; Horowitz-Kraus, Cicchino, Amiel, Holland & Breznitz, 2014), and the correlation of the ERN amplitude with numerous reading and cognitive difficulties in the dyslexic population, the ERN has been suggested as a possible biomarker for dyslexia. If we assume that the ERN is truly a biomarker that reflects the individual's reading impairment, can we suggest that a reading improvement following training will result in changes in the ERN?

2 Plasticity of Error Monitoring in Dyslexia and the Reading Acceleration Program

The Reading Acceleration Program (RAP) is a computerized reading intervention program that focuses on reading fluency (Breznitz, Shaul, Horowitz-Kraus, Sela Nevat et al., 2013). The program manipulates letter presentation rate, requiring the participants to read at their self-paced rate, while monitoring reading comprehension. Following several continuous successful trials, the program speeds the disappearance of letters from the screen, in an accelerated manner, tailored to the individual's reading pace [for more technical information see (Breznitz et al., 2013)]. The RAP has been shown to improve reading speed, and in some cases also accuracy, and comprehension in both children and adults with or without reading disabilities in several orthographies, including Hebrew (Horowitz-Kraus & Breznitz, 2011; Breznitz et al.., 2013; Horowitz-Kraus & Breznitz, 2013, Horowitz- Kraus, 2015; Horowitz-Kraus, Cicchino et al., 2014), English (Breznitz et al., 2013.; Niedo, Lee, Breznitz, & Berninger, 2014; Horowitz-Kraus, 2015; Horowitz-Kraus, Cicchino et al., 2014) German (Korinth, Dimigen, Sommer, & Breznitz, 2009), and Dutch (Snellings, van der Leij, de Jong, & Blok, 2009). The benefit of the RAP training is presumed to arise from a working-memory mechanism (Breznitz & Share, 1992; Niedo et al., 2014) as well as error-monitoring and attention abilities (Horowitz-Kraus & Breznitz, 2014; Horowitz-Kraus, Cicchino et al., 2014). During the reading process, units of data are integrated into the working-memory system at an increased rate and in more meaningful units for storage in the mental lexicon (Breznitz & Share, 1992; Horowitz-Kraus & Breznitz, 2014; Niedo et al., 2014.). A direct comparison of the effect of the RAP in either Hebrew or English revealed a greater effect on Hebrew-speaking children, which may be attributed to differences between Hebrew and English writing systems, given that the Hebrew-speaking children were trained on a shallow form of the Hebrew orthography as opposed to the deep English orthography (Horowitz-Kraus, Cicchino et al., 2014).

The RAP and Executive Functions

Several studies have demonstrated that the RAP improves the activation of the error-detection mechanism (Horowitz-Kraus & Breznitz, 2011, 2013); after 8 weeks of the RAP training, both children and adults with dyslexia as well as typical readers showed greater ERN and had a larger ERN/CRN gap during reading than prior to the RAP training. This improvement, which was positively correlated with the level of improvement in word reading scores, and with greater activation in the Anterior cingulate cortex (ACC)- where the ERN is evoked from as well as in the Fusiform gyrus which is considered as the visual word form area in the brain (Horowitz-Kraus, Vannest, Kadis, Cicchino, Wang et al., 2014), was thought to be due to increased storage and retrieval of words from the mental lexicon. This improved lexical processes may specifically be due to better error monitoring or is a general effect on the entire executive system. The effect of the RAP training on EF in children with dyslexia was examined using the Wisconsin task (Horowitz-Kraus, 2015). In this study, 12-year-old children showed an improved performance in the Wisconsin task, as well as smaller N100 amplitudes after training. The smaller N100 may reflect less attention resources needed to perform the task following RAP training, which was accompanied by improvement with other behavioral EF measures (working memory, switching and attention) and highlights the effect of the RAP training specifically on EF.

The Anatomical and Functional Correlates to the Effect of the RAP Training

Given that ERPs are the result of a neuronal activation over the scalp that may result from different brain regions, another interesting question was to examine the effect of the RAP training on regions of interest in reading-related neural circuitry by using a lexical decision task during fMRI. A specific question of interest was the involvement of the frontal lobe, and specifically of the ACC, following intervention. After 4 weeks of the RAP training, 8–12 year-old children with dyslexia showed improvements in reading comprehension that were associated with significant increases in right frontal-lobe activation. These results corresponded with previous findings pointing at positive correlations of white-matter tracts in the right frontal lobe with better reading comprehension scores in proficient readers (Horowitz-Kraus, Wang et al., 2014). Children with dyslexia also demonstrated greater activation in the ACC, which was the anatomical region from which the ERN is evoked after RAP training. This may position the ACC in general and the error detection mechanism in particular as a compensatory pathway for reading improvement (Horowitz-Kraus et al., 2013, Horowitz-Kraus & Breznitz, 2014). A further functional connectivity analysis suggested that the greater activation in frontal regions during reading in children with dyslexia, but the right ACC showed greater functional connectivity with the fusiform gyrus during word reading following reading training (Horowitz-Kraus, 2013). Additional studies demonstrated an increased functional connectivity between these two regions also during a resting-state condition (Horowitz-Kraus, 2015) as well as an overall increased functional connectivity within the cingulo-opercular network (which Is composed of the ACC) during rest in children with dyslexia following RAP training (Horowitz-Kraus, 2015). These results reinforce findings that greater activation of the error-monitoring system (in the ACC) is related to a more-efficient lexical processing (referred to as FG activation). Although a coupled EEG-fMRI study has not yet been performed, the author presumes that the activation of the ACC following the RAP training would be related to better monitoring performance during reading.

3 Closing Remarks

As researchers and clinicians continue to struggle to find underlying causes for dyslexia, in the past few years accumulated studies have indicated that impaired EF contribute to the existence and severity of dyslexia. With the development of neuroimaging tools, there are now more-sophisticated ways to objectively examine the association between different cognitive abilities, like reading and EF, in time and space. In a top-down cognitive control model, the EF system has been demonstrated to be anatomically divided into two different neural networks: the cingulo-opercular network for set-maintenance and the fronto-parietal for information processing (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008). These authors also described how reading relies in part on visual attention components that are located in the information processing network (precuneus). It is possible that individuals with dyslexia have a specific impairment in one of these networks and therefore compensation for one of them may result from a stronger functional connectivity with the other. Future neuroimaging studies should examine this point in depth. Another interesting question for future study is the effect of a specific EF training on neural circuits supporting both reading and EF. Is it possible that a specific training for the networks supporting EF would result in increased functional connectivity between reading and executive-related brain regions, as well as better reading outcomes? Future studies using fMRI would be useful for the investigation of this point. Nevertheless, this review highlights the important relationship between EF and reading, which is particularly relevant in the case of reading difficulties. Clinicians are urged to pay special attention to the EF domains when diagnosing and while tailoring interventions for those who suffer from reading difficulties.

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Why Does Prosody Accompany Fluency? Re-conceptualizing the Role of Phonology in Reading

Jane Ashby

Abstract This chapter addresses the observation that reading speed and reading intonation tend to develop together in typical readers, yet current theories of phonological processing do not explain this developmental relationship. To explore the connection between prosody and fluency, I first discuss skilled reading processes and then turn to the development of reading fluency in children. Recent eye movement data from skilled readers indicate that automatically processing prosodic phonological information speeds word recognition during silent reading. After differentiating between intentional decoding processes and automatic phonological precoding, I propose how precoding could shorten skilled word recognition time through a process termed prosodic constraint. A focused review of brain imaging studies discusses data consistent with prosodic constraint, and indicates the neural networks that could support it. Finally, I discuss the roles that several phonological processes could play in developing reading fluency.

Keywords Reading • Fluency • Prosody • Phonology • Eye movements • Reading development • Brain • Silent reading • Precoding • Constraint

Initially, beginning readers read quite slowly and without much expression. As a child's reading rate approaches the rate of speech, her oral reading aloud begins to carry the intonation and rhythm of speech as well. In other words, appropriate prosody often accompanies fluency. Conversely, dysfluent readers often read aloud with flattened or inappropriate intonation (Adams, 1990; Kuhn, Schwanenflugel, & Meisinger, 2010). Although prosody typically emerges along with fluency in reading development, reading theory has yet to explain why this occurs.

This chapter explores why prosody (intonation and rhythm) and fluency (reading speed) might develop hand-in-hand for most children. To provide a foundation for that exploration, I review a linguistic perspective on prosody in the phonological representations used in spoken language. Next, I discuss evidence of sub-lexical

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prosodic processing and how it contributes to the speed of skilled reading in adults. This review includes eye movement experiments and electrophysiological studies that suggest a role for phonological processing beyond that of decoding unfamiliar words; skilled readers also engage fast, prosodic phonological processes that help speed word recognition. I propose a processing account of how this occurs and review the cognitive neuroscience literature that suggests the brain networks involved. Based on these studies, I propose that prosody usually accompanies fluency in reading development because the phonological representations that support text-level prosody also support reading speed. The final discussion specifies the connection between prosody and fluency in young readers, proposing that several phonological processes operate in the different phases of fluency development.

Parents, educators, and psychologists often note the marked change that occurs as beginning readers' transition from reading accurately to reading accurately at the rate of speech (Adams, 1990; Chall, 1996; Goswami, 2000). Sometime in the first year or two of reading instruction, labored decoding and monotone pitch suddenly seems to switch to reading more quickly and with a speech-like intonation. Children who exhibit initial reading fluency at a younger age are exposed to more words per minute of reading than children who become fluent later. Thus, the ability to read fluently is a key contributor to a child's level of text exposure, which is one of the main predictors of reading achievement later in elementary school and beyond (Chall, 1996; Stanovich, 1986).

One characteristic of fluent reading fluency is prosody. The ability to read text prosodically (i.e., with a tone and rhythm that is appropriate for the meaning of the text) is a crucial goal for beginning reading (Breznitz, 2006; Connor, Alberto, Compton, & O'Connor, 2014; NICHD, 2000). During prosodic reading aloud, the voice rises and falls in pitch and pauses at the end of meaningful phrases. Adults read prosodically during silent reading as well; this is one aspect of inner speech (Abramson & Goldinger, 1997; Huey, 1908/1968). It is through inner speech that we are able to perceive a friend's voice in an email, to detect sarcasm, and to imbue characters with distinct voices when reading a novel. Prosodic processing, then, is central to the aesthetics of reading for pleasure. Given that improved prosody is integral to fluency development in typical readers, this chapter proposes one account of why that is the case.

Prosody is obligatory in human speech; children utter their first phrases with prosodic intonation. Thus, prosody comprises phonological characteristics that are integral to the *spoken* language system. As brain networks for reading develop, they utilize the neural architecture of spoken language systems. This shared language/reading architecture is illuminated by studies that examined the influence of literacy on speech processes (Reis & Castro-Caldas, 1997; Serniclaes, Ventura, Morais, & Kolinsky, 2005; Ventura, Kolinsky, Querido, Fernandes, & Morais, 2007). For example, Dehaene et al. (2010) found neural activity in areas associated with orthographic processing when skilled readers listened to speech. Nonreaders did not show such a pattern, which suggests that reading and speech networks become more interconnected as reading develops. Further, eye movement studies indicate that skilled readers impose speech-like intonation on text when reading silently (Ashby & Clifton, 2005; Breen & Clifton, 2011). These studies are just a few examples in an ample research literature indicating that reading processes piggy-back on language networks in skilled readers.

The ideas discussed here are grounded in the observation that improved prosody typically accompanies faster reading. Given that prosody is a characteristic of spoken language processing, the prosodic nature of fluent reading suggests a role for speech-based phonological processes in fluency acquisition. This chapter explores two main ideas: first, that skilled readers exploit speech-based representations to read text fluently; second, that improved prosody reflects a progressive alignment of reading processes with speech networks. I discuss what is known about phonological processing in skilled reading in order to better understand how changes in phonological processing could support fluency development in children.

The role of phonology in reading is complex. To lay the foundation for the discussion ahead, let's distinguish three aspects of phonological processing in reading: decoding, recoding, and precoding. Blythe (2014) describes decoding as the effortful process of grapheme to phoneme conversion that can occur overtly or covertly and is undertaken intentionally to identify an unfamiliar word. Frost (1998) uses phonological recoding to refer to the retrieval of an abstract phonological form from lexical memory for sentence integration. This chapter will use those terms accordingly. In addition, I apply the term *phonological precoding* to refer to the phonological processing that skilled readers typically engage to begin identifying words before they are fixated. Phonological precoding is the automatic processing of a word's probable phonological form that occurs parafoveally during silent reading. Precoding processes operate without readers' awareness during text reading, when lexicalized letter strings are present. Phonological precoding involves the fast and automatic phonological processing reported in the recent literature (see Halderman, Ashby, & Perfetti, 2012). There, we reviewed converging evidence for fast phonological processing, focusing on studies that found phonological processing in the first tenth of a second of visual word recognition. Here, I propose that phonological precoding reduces word recognition time during silent reading by streamlining lexical access before a word is actually fixated. Evidence for phonological precoding, how it functions in word recognition, and its relationship to reading speed and intonation is the focus of the first part of this chapter.

The relationship between phonological processing and fast word recognition is rarely considered in the literature. However, the fundamental relationship between phonology and fluency has been recognized for some time; children with stronger decoding skills read faster than children with poor decoding skills (Share, 1995), and those who have phonological deficits read slowly even as adults (Goswami, 2000). The next section discusses evidence that rapid word recognition involves skilled phonological processes that include sub-lexical prosodic information and operate early in lexical access.

1 Prosody in Skilled Reading

The word prosody originates from the Latin word *prosodia*, which means the stress of a syllable. In reading, prosody is defined as the imposition of the intonation, stress, and rhythm of speech onto written text. Although prosody is often noticed at the sentence level, prosodic contours are delivered through the duration, pitch, and intensity of the syllables in the words that make up the sentence (Ladd, 1996). For example, speakers place emphasis on a word by uttering its syllables at a higher pitch and for a longer duration. Therefore, linguistically-based perspectives generally consider sub-lexical units, such as syllables and even parts of syllables, to be prosodic constituents (Moats, 2010; Selkirk, 1982).

One characteristic of prosodic units is that they are organized hierarchically (Clements & Keyser, 1983; Frauenfelder & Lahiri, 1989). In English, a rhyme is nested in a syllable, one or more syllables are nested in a prosodic word, one or more words are nested in a rhythmic foot, and one or more feet are nested in a prosodic phrase. Figure 1 describes the sub-lexical, phonological structure of the spoken word *candy*. Prosodic units within this structure (such as syllables) are termed suprasegmental, as they span several phoneme segments. Years ago, Liberman, Shankweiler, & Liberman (1989) suggested that reading involves layered phonological representations that are similar to those used in speech. The studies discussed here offer evidence that this may be the case.

As skilled readers typically read prosodically, it is reasonable to inquire about how prosodic expression arises. Little is known about how sentence-level prosody emerges during reading. Intuitively, it may seem as though words are recognized first and then deliberately given prosodic features such as the rising tone on the last word in a question. Were this the case, then it should be possible to read text without intonation and phrasing. However if you try to read this paragraph without intonation, you will notice that it takes effort to do so. This suggests that although prosody can be separated from reading, it usually is not; prosody seems to be inherent to skilled reading.

A question remains, then, about the relationship between word recognition processes and prosodic text reading. If the representations used for lexical access

	CANDY				
Stress		1		0	
Syllable		kaen		di	
Rhyme		aen		i	
Phoneme	[k	ae	n	d	i]

Fig. 1 Layered phonological representations of spoken words include sublexical, prosodic information about syllable units and lexical stress

contain strings of phonemes but no prosodic information, then it is logical to assume that text-level prosodic intonation does not arise during word recognition. On the other hand, if readers represent sub-lexical, prosodic information en route to word recognition as Liberman et al. (1989) suggested, then the word recognition process itself could supply a foundation for expressive reading. In that case, prosody would be intrinsic to reading, arising during word recognition as well as during sentence integration.

The next section examines some evidence that skilled readers begin forming prosodic representations early in word recognition. In part, this evidence was obtained in studies that I conducted under the mentorship of Keith Rayner, Chuck Clifton, and Lisa Sanders at the University of Massachusetts at Amherst. These online reading studies measured eye movements and event-related potentials (ERPs), recording data many times a second during silent reading in order to provide a high-resolution picture of how skilled readers typically recognize words.

2 Do Skilled Readers Form Prosodic Representations Early in Word Recognition?

When reading sentences, skilled readers process the word they are looking at and begin processing the next word that they plan to fixate (Dodge, 1907). In English, the fixated word appears foveally and the word to its right falls in parafovea, which is an area of the visual field with reduced acuity. In Hebrew, it is the word to the left of the target that is processed parafoveally. Across writing systems, word recognition begins parafoveally in advance of fixation during text reading, yet readers generally are not aware of this (Rayner, 1998, 2009). When readers see text through a moving window that eliminates parafoveal processing of the next word, their reading is up to 25 % slower than when parafoveal information is available (see Rayner, Pollatsek, Ashby, & Clifton, 2012, for a discussion of this evidence). Therefore, parafoveal processing is a crucial part of reading fluency.

Eye movement studies provide a good indication of how skilled reading occurs outside of a laboratory setting, as participants in these studies read sentences silently and at their own pace. Given that readers are not aware of which words in the sentence are being studied, eye movement experiments provide information about the processes typically engaged to recognize words in context. By studying what phonological information affects fixation durations, we can understand how phonological processes function during silent reading.

We conducted several eye movement studies to investigate whether skilled readers used initial syllable information to identify words that appeared in sentences. These eye movement studies used a boundary-change technique called parafoveal preview to control the text readers saw parafoveally (Rayner, 1975). As seen in Fig. 2, the target region in each sentence initially contained a parafoveal preview (or prime) that was congruent or incongruent with the first syllable of the target word. When

Incongruent Condition

Before the Boundary Change

* |

The powerful ma_zxz astounded Indiana Jones.

After the Boundary Change

| *

The powerful magnet astounded Indiana Jones.

Fig. 2 The parafoveal preview paradigm. Parafoveal preview information is available during the fixation before the target (*). As the eyes move to fixate the target, they cross an invisible boundary (|) that triggers the display change. The change from preview to target completes during the eye movement, so that during the fixation readers see the target word

readers fixated the word before the target (T-1), preview information was available in the target location. While the eyes moved from T-1 to fixate the target, the parafoveal preview changed to the target word. As vision is suppressed while the eye moves, readers rarely notice anything awry in the text. We measured processing time for the target word when the preview was congruent with its first syllable as compared to when it was not. Crucially, the number of letters in the previews was identical in both conditions (across items).

Three eye movement studies examined whether skilled readers represent prosodic syllable information during silent reading in English. Ashby and Rayner (2004) tested this by presenting readers with parfoveal previews of target words embedded in sentences. Targets were preceded by previews that were congruent (de_xxx – demand, lan_xxx – lantern) and incongruent (dem_xx – demand, la_xxxx – lantern) with the first syllable of the target. Readers were slower to recognize targets in the incongruent conditions than in the congruent conditions, which indicates that they processed the parafoveal syllable information and used it to recognize the target word. Accurate parafoveal information about a word's initial syllable led to faster word recognition. Later studies confirmed and extended this syllable congruency effect in silent reading. Ashby (2006) found that syllable congruency affected the time to recognize high and low frequency targets. The two-letter syllable congruent prime led to faster word recognition than the three-letter syllable incongruent prime for the low frequency words and reading times were similar in both conditions for high frequency words. Ashby and Martin (2008) established that the syllable congruency effect can also arise in a parafoveal preview lexical decision task.

Together, the eye movement studies in English indicate that skilled readers typically represent sub-lexical phonological information about a word's prosodic form in the process of word recognition during silent reading. Syllable processing begins parafoveally, and occurs without the reader's awareness. Furthermore, a parafoveal preview of the correct first syllable speeds word recognition, indicating a role for sublexical, prosodic information in reading fluency.

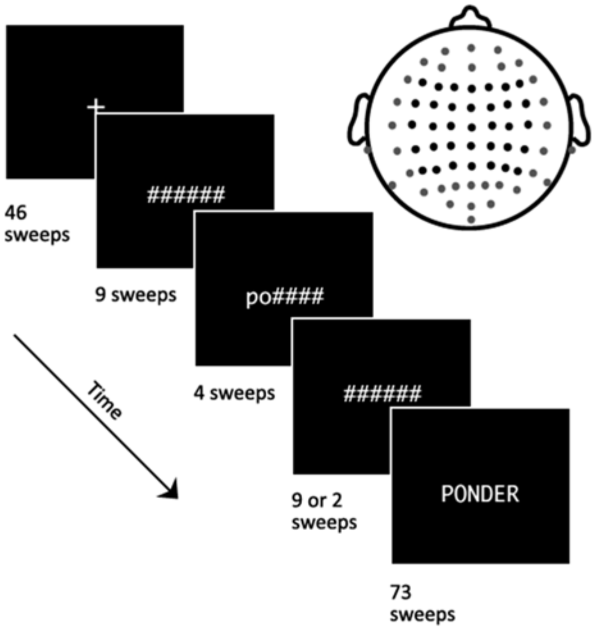

Fig. 3 The masked priming paradigm for single word reading (incongruent condition). Participants report seeing one ##### mask before the target appears

The English data converge with evidence from reading studies conducted in other languages. Eye movement studies and electrophysiological experiments conducted with readers of Spanish, German, French, and Chinese suggest that skilled word recognition involves processing syllable information (Álvarez, Carreiras, & Perea, 2004; Barber, Vergara, & Carreiras, 2004; Carreiras & Perea, 2002; Chen, Lin, & Ferrand, 2003; Chetail, Colin, & Content, 2012; Ferrand, 2000, Ferrand & New, 2003; Hutzler, Conrad, & Jacobs, 2005). Finding evidence of syllable representation in an opaque writing system (e.g., English) as well as more transparent writing systems (e.g., Spanish) suggests that sub-lexical, prosodic representations are a characteristic of skilled reading that spans orthographies. Exactly how these representations operate may vary across writing systems, however, and this is discussed later in the chapter. Finding that skilled readers can use syllable information to speed word recognition is consistent with previous studies indicating that speech and reading processes overlap in skilled reading, and it suggests that prosodic representations can operate pre-lexically in skilled reading.

In order to examine the time course of syllable processing more precisely, Ashby (2010) conducted two EEG experiments that recorded electrical potentials on the scalp continuously from the first moment a word appeared in order to register how quickly the brain processes syllable information during word recognition. The experiments investigated how soon the congruency of a syllable prime would modulate brain activity when reading a target word.

As seen in Fig. 3, masked priming provides a way to study the automatic phonological processes that occur during word recognition rather than intentional processes like decoding (Frost, 2003). Due to the short duration of the prime (<50 ms), readers reported seeing only the mask replaced by the target word. In the congruent prime conditions (ve###### – velocity, vel### – velvet), initial syllable information was correct and in the incongruent conditions (vel##### – velocity, ve#### – velvet) it was incorrect. Presenting the same primes and targets in the incongruent and congruent conditions (just in different combinations) meant that the visual stimuli were identical between conditions. Filler items were followed by questions, such as "is it bigger than toaster" to encourage full word identification. Event related potentials (ERPs) signaled brain activity in each condition, producing two waveforms at each electrode site that reflected the first half-second of word processing. If syllable congruency affected the word recognition process, then the waveforms in the congruent condition should diverge from those in the incongruent condition. The timing of this divergence would indicate when syllable congruency influenced the recognition of the target.

In both experiments, target words that followed primes with the identical first syllable elicited a smaller early negativity (N1) than targets that followed primes with one letter more or less than the first syllable. These syllable congruency effects appeared bilaterally at frontal and medial sites. The effects appeared by 100 ms when the prime-target interval was shorter, demonstrating that skilled readers processed initial syllables very early in word recognition. The time course of the syllable congruency effects indicates that readers processed initial syllable information during an early phase of word recognition, given that lexical access processes are thought to occur around 250 ms (Grainger, Kiyonaga, & Holcomb, 2006; Sereno & Rayner, 2003; Sereno, Rayner, & Posner, 1998). The phonological processing that yielded the congruency effects appears to be automatic in the sense that readers were not aware of the primes and nor were they asked to perform any explicitly phonological task (such as word naming or identifying rhyming words).

Ashby (2010) supports three conclusions: skilled phonological processing is fast enough to influence a very early phase of word recognition; it is automatic; and the early representations include prosodic units such as syllables. Given that prime-target congruency registers in brain electrical potentials 100–150 ms after a word appears, it is likely that the computation of congruency begins well before that time. The automaticity of skilled phonological processing is evinced by finding that syllable information in the prime shaped target identification even when readers were not aware of the prime. Lastly, finding syllable congruency effects in word recognition when initial phoneme overlap is controlled indicates the prosodic, hierarchical nature of these automatically generated representations. In all, finding that initial syllable congruency modulates brain activity in the first one/tenth of second suggests that skilled readers use sub-lexical prosodic information to recognize words.

In summary, the adult data indicate that the early activation of sub-lexical, prosodic information supports reading fluency by facilitating word recognition. The eye movement data demonstrate that skilled readers use parafoveal syllable information to reduce word recognition time during silent reading. The ERP evidence indicates that prosodic information at the syllable level modulates an early phase of word recognition. Together, these data suggest that phonological precoding supports both reading speed (by reducing word recognition time) and reading prosody (by representing suprasegmental, syllable information). Given these findings, it is not surprising that faster reading and improved prosody appear hand-in-hand in the course of normal reading development; both behaviors could emerge as readers increasingly use phonological precoding to recognize words during silent reading.

3 How Could Initial Syllable Processing Facilitate Word Recognition?

This section explores how prosodic phonological representations could shape lexical access during reading. Accumulating cross-linguistic evidence suggests that readers process syllable information during word recognition, but little is known about how they do that and why. Evidence for syllable processing is surprising, given that alphabetic writing systems do not explicitly denote syllable units (i.e., there are no spaces, dots or lines that mark syllable boundaries). This raises a question; how can readers process information that is not actually in the text? If syllable units are not visually marked, then readers may be anticipating the first syllable boundary based on implicit information in the text, such as familiar sequences of letters. It is unlikely that this anticipation is under the reader's conscious control (i.e., it is not an intentional "guess"), as controlled processes would appear much later in the ERP record. Rather, the early time course of the syllable congruency effect suggests that readers automatically activate an expectation of the phonological form of the word before it is fixated.

Provisional Representations

Prelexical, prosodic representations are likely to be probabilistic in nature. There are two reasons for this; one is the absence of graphemes that explicitly denote syllables (mentioned above) and another stems from limitations on visual perception. Visual information from the parafovea is usually incomplete and acuity diminishes rapidly, such that letters farther from the point of fixation are progressively more difficult to identify and discriminate (Rayner, 1998). This visual-perceptual limitation makes it difficult for readers to hold any definitive representation of a parafoveal word. However, readers could begin forming provisional representations based on parafoveal information. A provisional representation of a word's initial syllable, for example, would offer a head start on lexical access that would reduce the fixation time needed to identify that word. Therefore, phonological precoding is likely to involve the probabilistic activation of phonological information based on high frequency letter combinations.

Probabilistic representations are consistent with Bayesian-type models of word recognition, such as Bayesian Reader (Norris & Kinoshita, 2008). According to these models, readers use the available information to develop expectations about the lexical identity of a printed word. Of course these "expectations" are not intentional on the part of the reader, rather they arise automatically when readers detect letter strings that make up common initial syllables. Several Bayesian models are being developed as computational accounts of orthographic processing in word recognition (e.g., Norris, 2013).

Prosodic Constraint

The idea that the automatic activation of a provisional phonological form can shape word recognition and boost reading rate is a new conceptualization of the role of phonology in skilled word recognition that I refer to as *prosodic constraint*. Essentially, prosodic constraint occurs when parafoveal letter information activates a provisional phonological representation of the next letter string to be fixated. The probabilistic activation of sub-lexical prosodic codes (syllables, in this case) provides an additional stream of information that supplements the information available in the letter string. Readers could use the convergence of the provisional phonological form and the available orthographic information to constrain the set of possible lexical candidates. Prosodic constraint accounts for the eye movement and ERP evidence of early prosodic activation during silent reading, which many other theories of word recognition cannot accommodate. Further, it illuminates the utility of early syllable activation and explains how initial syllable processing could speed lexical access. Empirical studies are needed to test and refine this account into a formal theory; however the general idea of prosodic constraint is consistent with patterns emerging in the behavioral and neuroscience literature.

A cognitive system that uses common letter patterns to activate suprasegmental units that are a likely part of the phonological form could be quite efficient at recognizing words. By using orthographic pattern information to bias the system toward representing a specific initial syllable, readers could simplify the word recognition task. For example, the parafoveal letter pattern d-e-s would activate a number of lexical candidates (e.g., desire, desk, despair, desperado, describe, and destruct), but preferential activation of the syllable/*des*/would identify despair and desperado as the leading candidates. In this way, parafoveal orthographic information could be used to activate additional, suprasegmental information about the initial syllable. Together, orthographic information and syllable information would activate a smaller set of preferred representations than letter information alone and, thus, could shorten word recognition time. McClelland, Mirman, Bolger, and Khaitan (2014) presents an interactive activation model with Bayesian components, which offers a computational perspective that appears consistent with the concept of phonological constraint.

Prosodic constraint operates when letter information in a parafoveal preview or masked prime begins activating (or precoding) aspects of a word's suprasegmental phonology, thereby biasing the word recognition system toward letter strings that contain those suprasegmental units. The preferred syllable activation might begin as a boosted component of the larger cohort that is circumscribed by the letter string. Word recognition would be facilitated when the expected syllable was indeed the first syllable of the target, without incurring large costs when the preferred activation was not congruent with the target. Activating a suprasegmental unit before a word is fixated gives preference to the subset of possible candidates that are congruent with that provisional representation. In principle, this would facilitate word recognition by limiting the number of possible word forms.

Whereas syllable units are the main focus of this chapter, prosodic constraint may operate with other types of suprasegmental information as well, such as rime units comprising the vowel and any following consonants. In opaque orthographies, such as English, vowel letters are often phonologically ambiguous. Ambiguity logically leads to activation of a broad set of lexical candidates if only letter strings were processed. For example, the letter *a* in a four letter string would be expected to activate all such words containing an *a* in the rime unit (-ake, -ask, -amp, -all, -ate, etc.). However, a reader who perceived that vowel in the context of a common rime unit, such as *all*, could boost the activation of a smaller set of preferred candidates with that particular vowel sound (talk, wall, calm).

Kessler and Treiman (2001) conducted a corpus analyses indicating the existence of certain high frequency letter patterns in which the consonant coda effectively predicts the pronunciation of the vowel, and subsequent studies indicated that readers used these implicit cues to reduce ambiguity when reading and spelling pseudowords (e.g., Treiman, Kessler, & Bick, 2002, 2003). Evidence that college readers use parafoveal rime information appeared in Ashby, Treiman, Kessler, and Rayner (2006). We found that words were read more slowly when the preview's vowel sound was likely to be incongruent with the target (*rall – rack*) than when the preview's vowel sound was likely to be congruent with the vowel in the target (*raff – rack*). These data indicate that letter co-occurrence frequencies shaped an expectation of the vowel sound. Readers were sensitive to the clues that common sub-lexical orthographic patterns (e.g., all) can provide about a word's phonological form. By precoding some elements of phonological form during parafoveally processing, readers reduced vowel ambiguity and, thus, speeded word recognition. Together, evidence for the phonological precoding of rime and syllable information suggests that readers use whatever suprasegmental information is available in order to activate a preferred prosodic representation. Importantly, it also indicates that prosodic constraint speeds word recognition time for single syllable and multi-syllable words.

Breen and Clifton (2011) indicate that skilled readers represent the likely lexical stress pattern of an upcoming letter string as well as the initial vowel sound. Breen and Clifton monitored eye movements during silent reading and found that readers bias their representation of lexical stress pattern toward the pattern that is consistent with the most frequent form of stress-shifting homographs (ABstract), until parafoveal syntactic information requires a different part of speech (abSTRACT). When the expected phonological form did not fit syntactically, readers would revise the stress placement before reading on. This suggests that readers may synchronize other types of linguistic information (i.e., syntactic information) with a provisional phonological form before fixating a word.

Overall, the eye movement and ERP studies reviewed here indicate that skilled readers recognize words more quickly when a phonological expectation is correct than when the expectation is incorrect. These early, probabilistic representations include rime, initial syllable, and lexical stress information under certain conditions. Automatically activating phonological expectancies based on parafoveal information is the process of phonological precoding. This aspect of skilled phonological processing supports rapid word recognition, which is the foundation of reading fluency.

Benefits of Phonological Precoding

Precoding suprasegmental phonological information parafoveally could yield several benefits. Precoding allows readers to use a likely phonological representation *and* letter information to constrain the set of lexical candidates. Thus, the primary benefit of phonological precoding is reduced word recognition time. In addition, activating initial syllable information in advance of fixating a word would also sort out the probable sequence of the first few phonemes and letters, which could complement the position-flexible orthographic coding of letters proposed in recent models of orthographic processing (e.g., Grainger, Lété, Bertrand, Dufau, & Ziegler, 2012).

The benefits of phonological precoding may be modulated by the orthographic transparency of the writing system. In more opaque orthographies such as English, phonological precoding seems to supports rapid word recognition by reducing fixation time (Ashby & Rayner, 2004; Ashby, 2006). Phonological precoding may operate differently in more transparent orthographies such as Spanish, where the phonological representation of a letter string is unambiguous. In such cases, phonological precoding may reduce word recognition time by enabling readers to identify the initial syllable of a longer word *before* fixating it. In certain writing systems, precoding may be based on linguistic characteristics other than phonology. For example, precoding in Hebrew might be primarily morphological in nature. Readers could use the root information in parafoveal view to form provisional morphological representations that narrow the set of lexical possibilities for the next word to be fixated (Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2005).

To summarize, the present data from skilled reading indicate that skilled readers use phonological precoding to activate provisional prosodic information when reading in transparent and opaque orthographies. The specifics of how precoding supports fast word recognition may vary based on characteristics of the writing system. Syllable effects found in studies conducted in Spanish, German, and English indicate that phonological precoding includes sub-lexical, prosodic information. These provisional representations bias lexical access towards the most likely candidates in a cohort, based on the combination of prosodic and orthographic information. Thus, precoding the likely prosodic form of the next syllable to be fixated supports the efficiency of word recognition.

4 How Does the Brain Accomplish Prosodic Constraint?

One of the most exciting developments in reading research is the advent of methods for studying the brain bases of cognitive processes. Studies using functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and diffusion tensor imaging (DTI) provide information about the location and timing of phonological activation as well as the white matter tracts involved in word recognition. In this section, I discuss neurocognitive studies that suggest how prosodic constraint could operate in the brain of a skilled reader.

Two main brain areas appear active during skilled word reading; the inferior frontal gyrus (IFG) and the visual word form area (VWFA). Classic fMRI studies found IFG activity during word naming (Pugh et al., 1996, 1997), and a later meta-analysis confirmed that this area was consistently associated with phonological processing (Bookheimer, 2002). Cohen and colleagues reported data suggesting that the ventral occipito-temporal (vOT) region supports orthographic processing during word recognition in the VWFA (Cohen et al., 2000, 2002). Some word recognition theories (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) would predict that VWFA activation precedes the activation of phonology, as the orthographic-semantic route is assumed to be faster. On the other hand, the idea of prosodic constraint predicts that initial IFG activation would occur around the same time as VWFA activation.

Several MEG studies have registered activation in frontal speech areas in a time window that is consistent with phonological constraint. For example, Pammer et al., (2004) recorded brain activity during a backward masking, lexical decision task. Words and anagrams appeared for 100 ms followed by a mask, and subjects pressed a button to indicate whether they saw a word or a nonword. Pammer and colleagues reported two waves of activity: early occipital lobe activation (posterior to the VWFA), followed by activation in the visual word form area (VWFA) and in the inferior frontal gyrus (IFG). Importantly, the IFG activity during word reading appeared as early as the VWFA activity. Two other MEG studies reported similar early activity in the IFG that precedes or accompanies activation in the VWFA (Cornelissen et al., 2009; Wheat, Cornelissen, Frost, & Hansen, 2010). In particular, the Wheat and colleagues' data converge with the ERP data mentioned earlier to indicate that word recognition elicits activation in Broca's area as early as 100 ms post-target. Wheat et al. (2010) proposes that speech production codes mediate

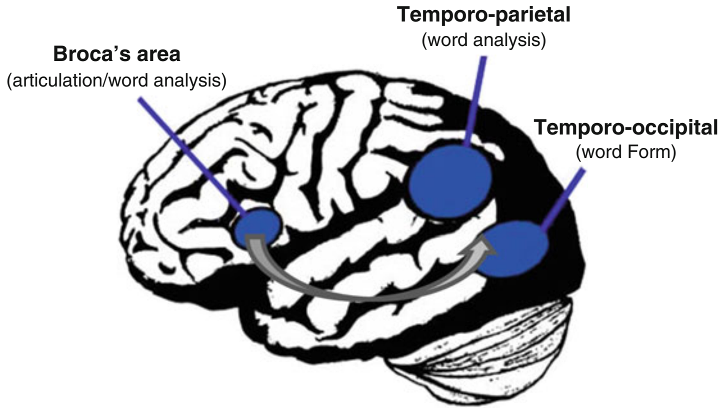

Fig. 4 The neural substrates of prosodic constraint. Activation of the expected initial syllable in Broca's area feeds back to constrain the set of potential targets activated in VWFA

word recognition, but does not explain how this process affects reading performance.

Additional evidence consistent with the idea of prosodic constraint appears in Price and Devlin (2011) and Woodhead et al. (2014). Woodhead and colleagues conducted a connectivity analysis of MEG data in order to examine the relative timing of activation in the IFG and VWFA. The difference between word and false font stimuli registered in connections from IFG to VWFA before 200 ms whereas the word vs. false-font difference appeared in VWFA to IFG connections at a later time. This suggests that frontal speech areas modulate lexical access processes in the posterior of the brain (see Fig. 4). Considering the early time window of the front-to-back activation and the involvement of a central phonological area, the initial frontal activation could reflect the automatic, rapid process of phonological precoding. Carreiras, Armstrong, Perea, and Frost (2014) discuss the front-to-back activation pattern in terms of interactive activation theory, but this otherwise informative paper does not illuminate how that pattern affects reading performance.

The present neurocognitive data appear consistent with the concept of prosodic constraint initially indicated by eye movement studies. In addition, these data reveal a possible network of skilled word recognition processes that allow the phonological information to automatically facilitate word identification. Whether the activation found in MEG studies reflects processes that are similar to those observed in the eye movement and ERP studies is not certain; however there are no inconsistencies that would rule out that conclusion. The phonological activation reported in the eye movement studies appears similar in timing and content. The timing of the early phonological activation found in MEG studies coincides with the timing of syllable congruency effects in the previously discussed ERP studies (before 200 ms). Thus, studies converge on when phonological activation shapes word recognition. Finding activation in Broca's area suggests the involvement of production codes, which are thought to be syllable-based (Cholin, Dell, & Levelt, 2011). The eye movement data demonstrate that the phonological precoding of syllable information reduces word processing time and, thereby, complement the MEG data by revealing how early phonological activation affects reading behavior. Together, the neurophysiological data and the eye movement data advance our understanding of visual word recognition by (a) describing the timing of neural activity that underlies phonological and orthographic processes and (b) demonstrating the utility of early phonological activation, which is to speed word recognition during text reading.

If the frontal speech areas do modulate the recognition of letter strings, then one would expect to find a white matter tract of axons connecting Broca's area with the visual word form area. Yeatman, Rauschecker, and Wandell (2013) used diffusion tensor imaging to identify a white matter bundle in skilled readers that connects BA45 (inferior frontal gyrus) with the VWFA. In other words, skilled readers have a neurological pathway between an anterior area dedicated to speech processing and a posterior word recognition area. On the surface, this seems consistent with prosodic constraint. However, Yeatman and colleagues found the ventral pathway to VWFA to originate in BA45. Whereas some studies suggest that BA44 is involved in phonological coding and BA45/47 supports semantic processing (e.g., Poldrack et al., 1999), others report phonological activation throughout BA44/45 (e.g., Heim, Eickhoff, & Amunts, 2008; Heim, Ischebeck, Friederici, Stephan, & Amunts, 2009). In any case, the extensive connectivity between BA44 and BA45 could transmit phonological information to the VWFA indirectly via BA45. Thus, white matter studies suggest that over years of text reading experience, skilled readers develop the neural connectivity between IFG and VWFA that would allow prosodic representations to constrain the set of lexical candidates activated by a letter string.

To summarize, imaging studies indicate that the location, timing, and connectivity of the ventral network connecting Broca's area and the visual word form area make it possible to observe the syllable congruency effects that suggest phonological precoding. Prosodic constraint theory describes a cognitive mechanism that is consistent with the early activation of the IFG observed in imaging studies, the front-to-back pattern of neural activity that appears in connectivity studies, and the white matter tracts identified with diffusion tensor imaging. Furthermore, it suggests how this neural activity could support fast word recognition during silent reading by incorporating evidence of phonological precoding of syllables, which are fundamental production units in English (Cholin et al., 2011). During text reading, the automatic activation of syllable-based production codes that occurs in IFG before a word is fixated could support the phonological precoding that speeds word recognition during text reading. Skilled readers may activate the abstract syllable units used in speech production in order to favor a subset of possible lexical candidates. The integration of neurophysiological data and behavioral data affords a novel take on the relationship between skilled phonological processing and reading speed, as it implicates cortical areas known to be active during reading that could support prosodic, phonological constraint. If prosodic expectations of phonological form speed word recognition, then this relationship could explain the coincidence of prosody and fluency in typical reading development. Given the previous discussion of how skilled phonological processing supports reading fluency in adult readers, let us now consider the possible role of phonological precoding and prosodic constraint in the growth of reading fluency.

5 Phonological Processing and Fluency in Reading Development

Over the course of reading development, many children progress from guessing at words to slowly decoding them, and then to reading them quickly and easily. Those who become fluent readers gradually develop the automatic processes that skilled readers use to recognize words efficiently and maximize reading rate. This process occurs over a time span of years for readers of English, but may happen faster for children learning to read more transparent writing systems, such as Spanish.

Fluency development rarely is a seamless, homogenous process in which reading speed accelerates at a consistent rate. More frequently, the trajectory of fluency development in typical readers includes noticeable shifts in reading behavior that may mark underlying changes in neural networks and the cognitive processes they support. Therefore, it may be helpful to consider fluency development in several phases: initial fluency, an interim phase, and full fluency. The next sections discuss each phase in terms of the characteristic reading behaviors, the development of neural networks for reading, and what neural development suggests about the role of phonological processing in that particular phase of fluency development.

Initial Reading Fluency

Initial fluency is the first notable jump in reading fluency. It occurs in the first or second year of reading instruction in English. Typically, an increase in reading speed appears in tandem with improved prosody, which helps the reading sound more expressive than it might prior to initial fluency, when decoding is slow and effortful (Kuhn et al., 2010). Although reading sounds increasing speech-like, it remains effortful for many children and can cause them to tire after just a few minutes of reading (Chall, 1996).

Let's consider how the brain supports these developments in initial reading fluency. Decoding processes operate serially and slowly at first. Initially, younger readers showed more activity in diffuse areas bilaterally, but brain activity becomes more focused in the left anterior and dorsal circuits as reading develops (Shaywitz et al., 2002, 2007). Ashby and Rayner (2012) reviewed evidence that a dorsal reading circuit involving Wernicke's area and the angular gyrus supports phonological decoding. Activity in this dorsal circuit is soon accompanied by another, anterior circuit that involves the inferior frontal gyrus (Pugh et al., 2001). Within the first year or two of reading instruction, these circuits in the left hemisphere become increasingly active during word recognition (Frost et al., 2009). The correspondence between these developments in brain circuitry and the onset of initial reading fluency is interesting to note. Perhaps the coordination of letter-sound mapping processes in the dorsal circuit with speech production processes in the anterior circuit underlies the prosody-fluency connection that is apparent in the early years of reading instruction.

The connection between phonological decoding and learning to read is well-supported in the literature; decoding helps children map printed words onto spoken words that they know (Share, 1995, 2011). As decoding skills develop fully, the process of serially decoding words focuses attention on all of the letters in a printed word, which establishes a precise lexical representation that can be accessed quickly during future reading (Ehri, 1998, 1999; Ehri & Wilce, 1985). For example, Sprenger-Charolles, Siegel, Béchennec, and Serniclaes (2003) conducted a longitudinal study of children in grades 1–4, which found that decoding early in Grade 1 predicted orthographic knowledge in Grade 4. One interpretation of this result is that accurate decoders have more detailed representations of printed words, which allows them to recognize frequently occurring letter patterns. This orthographic knowledge further enriches the lexical representations of words and contributes to word reading efficiency.

The speed of decoding is as important as accuracy. Faster readers see more words repeatedly and more new words in any given reading period than slower readers do (Stanovich, 1986). The increased text exposure that fast decoders experience further increases their store of familiar words. Familiar words are recognized quickly using stored representations (Frost, 1998). Therefore, having detailed representations of familiar words stored in memory allows young readers to access words from memory as well as by decoding, thereby reducing the time and effort devoted to word recognition (Perfetti, 1985).

The Interim Phase

The interim phase of reading fluency is characterized by the ability to read fluently, or at the rate of speech. In English, most children can do this by the end of second grade or third grade. Therefore, this phase may span the ages of 7 through 10 in readers of English. During these years, reading rate continues to improve as children keep decoding unfamiliar words and further expand their memory store of familiar words.

In the interim phase, the relationship between the dorsal network connectivity and reading skill changes. Whereas better reading in the initial fluency phase correlated with more activity in the dorsal network, better reading a few years later is accompanied by less activity in the dorsal network than appeared for worse readers. Similarly, adult readers with better word recognition skills exhibited less activity in the frontal circuit when reading novel letter strings than adults who were poorer readers, which suggests that reduced frontal activity reflects more efficient decoding (Frost et al., 2009; Sandak et al., 2004).

In addition, activity in the posterior of the brain (vOT) during word reading gradually becomes more lateralized to the left hemisphere during this time (Marcel, Katz, & Smith, 1974). Imaging studies suggest that it takes years of reading experience for the visual word form area (VWFA) of vOT to become maximally lateralized. Dundas, Plaut, and Behrmann (2012) studied vOT activity during face recognition and word reading tasks in children, adolescents, and adults. During word recognition, children exhibited activity in the visual form area and its right hemisphere homolog even after 3 years of reading instruction in English. Furthermore, Dundas, Plaut, and Behrmann (2012) found that the strength and lateralization of the VWFA activity during word reading correlated with reading skill in each age-group, with adults having the most lateralized activity. Therefore, it appears that for typical readers of English, the left vOT becomes specialized for reading words after several years of reading experience. Increasing fluency in this interim phase involves a shifting of bilateral activity during word processing to primarily left hemisphere activity. This lateralization brings posterior, vOT activity in closer proximity to language circuits including IFG. If the lateralization of vOT activity reflects an accumulation of orthographic knowledge in the reading brain, then the timing of lateralization suggests that the orthographic lexicon is a product of text exposure.

As children begin to recognize more words as familiar, they use phonological recoding during reading more often than decoding. Around this time, phonological processing speed begins contributing to growth in reading fluency. For example, Ashby, Dix, Bontrager, Dey, and Archer (2013) monitored eye movements during picture matching (phonemic awareness tasks and a receptive spelling task) and silent reading for comprehension. The time to look at the correct spelling of a spoken word predicted reading fluency within second grade, but did not account for much variance in third grade fluency. However, reading fluency in third grade was predicted by phonological processing time in second grade; children who looked more quickly at the picture ending with the same last sound as the spoken target were faster readers one year later than children who took longer to identify the matching picture. Therefore, processing speed during an auditory phonological awareness task supported silent reading fluency in the following year.

Full Fluency

When children can read text effortlessly for a long period of time, they have reached a state of full fluency. For children who achieve full fluency, the words on the page fade from awareness during reading and they seem to access the content as easily as if they were listening. Full fluency ushers in voracious reading habits; it is the hallmark of a successful reading education.

Around the age of ten, children's eye movements during reading are nearly indistinguishable from adult eye movements (Rayner et al., 2012). When reading grade-level text, the timing of fixations and the number of fixations track the pattern seen in adult readers. Also, the perceptual span is about as large at this age as it is in adults, which allows the parafoveal processing of words. Interestingly, neuroimaging studies of readers at this age indicate that activity in the IFG begins to be accompanied by vOT activity (see Schlaggar & McCandliss, 2007, for a review). Recall that in adult readers, white matter tracts also connect the IFG with the visual word form area in vOT (Yeatman, Rauschecker, & Wandell, 2013). This inferior frontal – occipital reading circuit could provide a neural basis for full reading fluency, as it allows the anticipatory activation of syllable information in the parafovea to constrain word recognition. Consistent with this idea, Shaywitz et al. (2002, 2007) indicates that better readers around age 10 have more connectivity in this ventral network than worse readers have.

Savvy readers will note that the ventral reading route establishes at a later point in reading development than the dorsal route for decoding (Pugh et al., 2001). The timing of these changes in functional specialization and connectivity coincides with qualitative changes in reading behavior that mark shifts in fluency development. Prior to reaching full fluency, children may sound fluent but tire after reading a few pages of text. Once connections between IFG and the VWFA are established, however, children read silently more quickly than they can speak and they can read for hours at a time. The change in ease and pace of reading that accompanies full fluency suggests that a reorganization of the reading system occurs that achieves maximum word reading efficiency. The data suggest that this reorganization entails early activation in the front-to-back network, which supports rapid integration of the available letter information and phonological precoding.

Does Phonological Processing Change with Reading Development?

The previous discussion of how reading circuits develop in the brain at different points in development also suggests that "phonological processing" comprises distinct processes. For example, recall the evidence that Broca's area activity accompanies dorsal circuit activity early in reading development when children rely on decoding processes. In contrast, skilled readers who rarely use decoding exhibit activity in the ventral network that connect Broca's area and the VWFA (Pammer et al., 2004; Price & Devlin, 2011; Woodhead et al. 2014). In both the child studies and the adult studies, activity in Broca's area accompanied word recognition. However, this frontal activity appears to correlate with different brain areas in early readers than in skilled readers. This suggests that brain networks support several phonological processes that come "online" at different times and make distinct contributions to word recognition. One phonological process mainly supports word decoding whereas another shapes the recognition of familiar words through phonological precoding and prosodic constraint. This suggests that phonological processes contribute to reading fluency in children and in adults, but the nature of the most prevalent type of phonological processing changes as reading skill develops.

Throughout reading development, the changing nature of phonological processing is supported by cortical plasticity, which in turn manifests as qualitative changes in reading fluency. Beginning readers use decoding to read the many new words they encounter, and this processing is supported by coordinated activity in the angular gyrus and IFG that supports deliberate letter-sound mapping that activates abstract speech codes. Fully alphabetic, serial decoding emerges as connectivity in the dorsal network increases to support initial fluency. This contributes to the later development of other networks by increasing awareness of frequent letter patterns and their corresponding phonological forms. When children achieve the effortless reading that signals full fluency, they process most words parafoveally, using phonological precoding to generate a likely representation of a word's prosodic form that is communicated back to VWFA. This representation speeds lexical access by activating a smaller, preferred set of possible candidates indicated by the letter string, according to prosodic constraint theory.

6 Summary

A definitive understanding of the neural architecture and cognitive processes that underlie reading fluency is beyond the reach of the current literature. Here, I have attempted to construct a coherent working story of why prosody typically accompanies reading fluency. This story connects evidence from several reading research paradigms to yield a fresh perspective on reading development that is consistent with the present literature. A story's setting allows for certain plot developments and precludes others. This story may be limited by its setting in the land of English. Nonetheless, it describes evidence for fast and automatic phonological precoding, proposes a theory of how precoding functions to support reading fluency, situates precoding in a neural network for reading, and reveals how developing networks involving Broca's area could project speech-based representations that support fluency at several points in reading development.

Here is a brief synopsis. Eye movement studies indicate that parafoveal syllable processing contributes to the rapid rate of skilled silent reading. This phonological precoding is the automatic cognitive process of building an implicit expectation of a word's phonological form based on information that is available parafoveally. Predictions of sublexical, prosodic characteristics (such as syllable information) shape early lexical access processes by supplementing the orthographic information available from the first few letters of a parafoveal word. Automatically generated expectations of the likely prosodic form supplement the available letter information and preferentially activate a subset of the lexical candidates that were denoted by the letter string alone, thus speeding word recognition. The consistent timing of early phonological effects in ERP and MEG studies suggests that phonological precoding of the first syllable in a written word involves early IFG activation. Evidence that the activation of syllable and rime information during silent reading reduces word recognition time suggests a link between aspects of phonological processing and reading fluency. In other words, pre-lexical prosody appears to enable reading fluency by reducing word recognition time.

The early contribution of speech-based representations to visual word recognition could also feed the text-level prosody that typically accompanies fluent reading. Sub-lexical prosodic information could serve as a foundation for appropriate intonation and phrasing during oral reading. This may explain why typically developing readers begin to read more expressively as their reading speed accelerates; sub-lexical prosodic information could contribute to both intonation and reading speed. Once a word has been identified, the prosodic representations involved in phonological precoding could be repurposed to contribute to the experience of inner speech during silent reading.

This working story provides a coherent explanation for why prosody and fluency appear to develop hand-in-hand, at least for typical readers. It reveals possible connections between skilled phonological processing and reading speed that are rarely discussed in the reading literature. It tracks the accumulating evidence for changing roles of phonology in reading development and illuminates how emerging reading behaviors could reflect changes in neural organization. Admittedly, there is little direct evidence to support this story. However, it is consistent with data from many studies. Better stories may be proposed to account for the existing data, and I look forward to hearing them.

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The Basis of Reading Fluency in First Grade of Hebrew Speaking Children

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Abstract The present study examines the contributions of several different cognitive and literacy skills to reading fluency in Hebrew among Grade 1 students. The main objective of the study was to examine what predicts word reading fluency at two crucial points during Grade 1: mid-year, before a multi-tiered intervention, and again 12 weeks later at the end of the year, after the intervention. A total of 47 first graders in Israel were assessed on cognitive and literacy tasks before and after an implementation of intervention. Our preliminary results demonstrate that in Hebrew orthography, there is a rapid growth in word reading fluency during Grade 1. One skill, syllable deletion, predicts reading fluency by the middle of Grade 1. By the end of Grade 1, two skills predict word reading fluency: RAN and syllable deletion. The results call attention to the pedagogical need to monitor this skill in Hebrew and emphasize the need to include fluency theoretically in models of reading as well as in related practice of early reading development in Hebrew orthography.

Keywords Fluency • Grade 1 • Word reading • Hebrew orthography • Early development of reading • Reading

1 Introduction

In 1981 the late Prof. Zvia Breznitz published her doctoral dissertation which focused on reading fluency in first grade. She was a pioneer in her field and understood the importance of fluency many decades before the topic became main stream in reading research. Not only did she conduct cognitive, and intervention studies for

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her dissertation, she also conducted teacher interviews. One of the most interesting findings of her dissertation was the negative attitude teachers have towards focusing on reading rate. Prof. Breznitz continued her passion for fluency research and intervention for over three more decades and her work influenced thousands of children around the world. In this chapter which we dedicate to her memory, we wish to continue her work and to push forward the idea that fluency, especially in the Hebrew orthography, must be given more stress and focus. This chapter will examine reading fluency skill in Hebrew orthography as well as the underline processes that contribute to fluency at the very early age of acquisition in the first grade.

A meta-analysis conducted by the National Reading Panel (2000) demonstrated that reading fluency is one of the key components to success in reading and that it is essential that it be taught to developing readers. Since the beginning of the twenty-first century, reading fluency has taken its place with phonemic awareness, word decoding, vocabulary, and comprehension as critical components of effective reading instruction (Rasinski, Blachowicz, & Lems, 2012).

Oral reading fluency is a complicated, multifaceted process that involves the coordination of many processes and sub skills involved in reading (Wolf & Katzir-Cohen, 2001). Most of the research on the development of reading fluency has focused on the English orthography and on later stages of reading acquisition, especially in second and third grade. In this chapter, we wish to examine the role of fluency in a relatively unstudied orthography – Hebrew. In addition, we wish to track the onset of the development of reading fluency from the beginning of first grade. In this chapter we will first review definitions of fluency, then the possible predictors of word reading fluency, the characteristics of Hebrew orthography and the development of word reading in Hebrew.

Researchers have begun to broaden the definition of fluency beyond a simple calculation of the rate of correctly read words. For example, Wolf and Katzir-Cohen (2001) defined fluency as integrated with developmental and componential processes. According to their definition, developing reading fluency is the product of the initial development of accuracy and the subsequent development of automaticity in underlying sublexical processes, lexical processes, and their integration in single-word reading and connected-text reading. These include perceptual, phonological, orthographic, and morphological processes at the letter, letter-pattern, and word levels, as well as semantic and syntactic processes at the word level and connected-text level. In line with Wolf and Katzir, Hudson, Pullen, Lane, and Torgesen (2008), suggested that fluent reading is the result of a large number of sub-processes that must be accomplished efficiently and automatically and that interact with each other. These include automatic access to letter-sound relationships, quick and accurate operation of phonemic analysis and blending processes, automatic access to knowledge of phonograms, a large number of words that can be recognized “by sight”, quick access to vocabulary knowledge, and efficient operation of basic information processes.

Historically, the study of reading has focused largely on accuracy in single word reading, rather than on the accurate and rapid reading of connected text (Kame’enui & Simmons, 2001). Thus, a conception of fluency that focused on the combination and outcome of speed and accuracy at the word level was considered an indicator of overall reading competence (e.g., Fuchs, Fuchs, Hosp, & Jenkins, 2001; Meyer &

Felton, 1999). Consequently, fluency is often measured by the number of correct words read aloud in 1 min (e.g., Fuchs, Fuchs, & Maxwell, 1988; Shinn, Good, Knutson, Tilly, & Collins, 1992; Torgesen, Rashotte, & Alexander, 2001). According to the NRP, accuracy is universally assumed to precede rate in development (National Reading Panel (US), National Institute of Child Health, & Human Development (US) (US), 2000). However, it is interesting to examine whether accuracy is acquired at different timing in different orthographies.

Possible Predictors of Word Level Fluency

Based on the current definitions that place fluency as the outcome of multiple lower level processes, many studies across different orthographies have found phonological processing, rapid letter naming, working memory, vocabulary and dictation to be good predictors of reading, especially in regular orthographies. Phonological awareness (PA) is the ability to manipulate the sounds in spoken language. Phonological awareness has been found to be a strong predictor of reading fluency in many languages such as English (MacDonald, Sullivan, & Watkins, 2013; Papadimitriou & Vlachos, 2014; Solari et al., 2014), French, Dutch, Hungarian (Vaessen, Bertrand, Denes, & Blomert, 2010), and German (Landerl & Wimmer, 2008). Recent studies have examined the universal and language-specific roles of PA in different languages. For example, an examination of the word reading skills of second graders in five different European languages of varying degrees of transparency demonstrated that phonological awareness was the main factor associated with early word reading performance, although its impact was modulated by the transparency of the orthography, such that PA had a higher impact in less transparent orthographies (Ziegler et al., 2010).

Another main predictor of fluency is Rapid Automatized Naming (RAN), as speed is an important component of both fluent reading and rapid naming (Cardoso-Martins & Pennington, 2004). It has been consistently found to be related to fluency of reading in English (Bowers, 1995; Cardoso-Martins & Pennington, 2004; Katzir et al., 2006; Morris et al., 1998; Pennington, Cardoso-Martins, Green, & Lefly, 2001) as well as in other languages, such as Finnish (Koponen, Salmi, Eklund, & Aro, 2013), Italian (Tobia & Marzocchi, 2014), German (Landerl & Wimmer, 2008), French, Dutch, and Hungarian (Vaessen et al., 2010).

While some studies point to similar predictive power across languages for PA and RAN (Caravolas et al., 2012; Furnes & Samuelsson, 2011; Vaessen et al., 2010), others have shown that the roles of PA and RAN are not the same in all orthographies. For example, Mann and Wimmer (2002) examined 100 German children and 60 American children at the end of kindergarten, first grade, and second grade. They found that phonological awareness was the only significant predictor of reading accuracy and speed in English. In German, however, RAN was the only significant predictor of reading speed. Furthermore, in a study of 110 English-speaking children and 70 Greek-speaking children in first grade, RAN was a predictor of later reading fluency in English in second grade, but this was not the case in Greek (Georgiou, Parrila, & Papadopoulos, 2008). It seems possible that while they have both been proven to be important to reading, PA and RAN play different roles at different points in time and in different orthographies.

Hebrew Orthography

Reading instruction of the pointed Hebrew script takes place in Grades 1 and 2. In pointed Hebrew, diacritics carrying most of the vowel information of a word are present with the consonant letters of the word. This allows a nearly unambiguous conversion of spelling to sound. In Grades 3 and 4, children are expected to gradually proceed to reading without vowel diacritics. In the absence of diacritics, orthographic ambiguity is frequent. Some textbooks presented during this 2-year transitional period are printed in a partially pointed script containing only some diacritics. By the end of Grade 4, children are expected to have mastered reading of the unpointed script, and from Grade 5 onward, readers of Hebrew are exposed almost exclusively to unpointed texts.

Reading Development in Hebrew

Several studies examined the relationships between PA and reading in first grade. Bentin and Leshem (1993) reported a strong correlation between PA and Hebrew reading by the middle of first grade. Share (2008) suggested that, at this point in development, decoding skill in Hebrew orthography may be more comparable to that of English speakers later in the year.

There are few studies of reading fluency development in Hebrew. Shany, Bar-On, and Katzir (2012) examined the development of reading in Hebrew orthography in the pointed script, of a nationally representative sample of children in Grades 2, 4, and 6. Rate and accuracy for four different pointed orthographic structures were collected: letter-diacritic mark combinations, legal pseudowords, illegal pseudowords, and real words. The results indicate that rate develops linearly from Grade 2 through Grades 4 and 6 with respect to all four orthographic structures. However, steep development was demonstrated for word reading rate, as compared to moderate progress for the other two structures.

Bar-Kochva and Breznitz's work so far has been the only one that examined the longitudinal trajectory of word reading fluency development in Hebrew (Bar-Kochva 2011; Bar-Kochva 2011, 2013). Their first longitudinal study examined children from kindergarten until the end of second grade (Bar-Kochva 2011; Bar-Kochva & Breznitz 2014). As reported, fluency of silent word reading and oral text reading measures improved from first grade to second grade. However, oral word reading fluency was not enhanced. Among first and second grade students, RAN contributed to fluency measures. Interestingly, the contribution of phonological awareness to fluency measures in first grade, decreased in second grade. In a second study, they examined Hebrew readers transitioning from the third to the fourth grade (Bar-Kochva & Breznitz, 2014). Phonological awareness explained a considerable amount of variance in accuracy in reading all forms of script across these 2 years. The role of RAN in fluency in reading the pointed and partially pointed forms of script was significant and similar in both grades, whereas the role of RAN in fluency in reading the unpointed script was restricted to Grade 4. In addition, the relations between phonological awareness and fluency in reading were restricted to Grade 4. The reason for these developmental fluctuations is hard to deduce from the current data. These patterns are different from learning to read in a less transparent orthography like English and may be influenced from the shift from reading pointed to unpointed Hebrew in fourth grade. Katzir, Schiff, and Kim (2012) conducted a within- and between-group comparison of word reading fluency and accuracy among fourth grade English and Hebrew-speaking children, respectively, as well as an examination of the role of phonological awareness in predicting word reading in each language. For Hebrew-speaking children, phonological awareness added unique variance to timed vowelized and unvowelized word reading measures (i.e., TOWRE in Hebrew; 11 % and 13 % respectively) after controlling for vocabulary. For English-speaking children, phonological awareness did not add any significant Variance after accounting for vocabulary knowledge in both timed and untimed word reading. They conclude that there are orthography-based processes at play and that learning to read in different orthographies creates differences in reading fluency and accuracy even at the later stages of reading in fourth grade.

Thus, whereas in shallow orthographies the grapheme-phoneme conversion is efficient, deep orthographies demand identification of larger orthographic units than letters. Shany et al. (2012) claimed that orthography might affect the timing at which accuracy is acquired among novice readers. The study of Caravolas, Lervåg, Defior, Málková, and Hulme (2013) confirmed this claim. In this study a cross-linguistic comparison of growth in reading was made between consistent and inconsistent orthographies. English speakers (i.e., inconsistent orthography) from reception year and Czech and Spanish speakers (i.e., consistent orthographies) from final kindergarten year participated until the end of second grade. A main result of this study was slower growth and development in English reading compared to more consistent orthographies. In this context, Hebrew orthography which contains two versions of script, a transparent (i.e., vowelized) and an opaque (i.e., unvowelized) script, appears to be a unique case for examination (Katzir et al., 2012).

Hebrew readers acquire reading by using the shallow pointed system (Shany et al., 2012), a system that is classified as consistent orthography (Katzir et al., 2012). Therefore, at the end of first grade they are expected to achieve proficiency in decoding (Share & Levin, 1999). However, Share and Levin (1999) pointed out to the rapid mastery of learning to read Hebrew compared to English. Thus, accuracy of decoding among Israeli children in first grade was found comparable to the performance of English children in grade 5.

In conclusion, fluency is much effected by the transparency of the orthography, both in the rate of development as well as in the factors that influence it in different stages of development. Our study took a very fine grained look at a wide array of factors cognitive and linguistic ones that may influence reading fluency development at the early stages of reading acquisition in Hebrew.

2 Current Study

Most studies on word reading fluency have been conducted on English-speaking children (Share, 2008) reading the notoriously opaque English orthography. In view of the differences found between different orthographies, there is a need for more examination of the development of reading fluency skills in more consistent writing systems, such as Hebrew. In addition, it is necessary to explore the development of this crucial skill, especially during the first grade in Hebrew, since it is expected to be acquired fast due to the consistency of the orthography. The present study examines the contributions of several different cognitive and literacy skills to reading fluency in Hebrew among first grade students. The main objective of the study was to examine what predicts word reading fluency at two crucial points during first grade: mid-year, before a multi-tiered intervention, and again 12 weeks later at the end of the year, after the intervention. Four research questions guided the current study:

1. What is the course of development of word reading fluency in Hebrew during first grade?
2. Which lower level components included in recent definitions of fluency (phonological awareness, rapid naming, etc.) are associated with word reading fluency by the middle of first grade and by the end of first grade?
3. What skills from the middle of first grade predict word reading fluency at the same point in time?
4. What skills from the end of first grade predict word reading fluency at the same point in time?

Intervention

In this study we administered a pilot intervention program (Lipka, Katzir, & Shaul, in preparation) which addresses the multiple sources of word reading difficulties in children. The main goal of the "OR" innovative intervention program for the first grade was to promote foundational literacy, cognition and emotionally readiness for learning skills by integrating for the first time those three domains into a range of cyclical activities.

The intervention consists of two books/themes per unit and each unit consists of nine scripted lesson plans. Overall, a total of 18 intervention sessions were given.

The program was implemented twice a week in each classroom for a period of 45 min in the second half of the year within the school hours for 3 months.

Children were first screened in order to build a cognitive and linguistic profile for each child. Then they were grouped into small homogeneous groups of five children based on their cognitive, literacy and emotional readiness profiles described below. The whole class worked on a similar shared book, yet each group received intervention around their needs in decoding, vocabulary, memory, and at a level which was matched to their ability. All the children in the classroom received the intervention at the same time on the same time slot. All the children participated in all sessions.

The program was delivered by the homeroom teacher, who led each lesson and by three trained master students that were specialized in literacy. Both teachers and students received specific training on the program materials.

3 Method

Participants

Participants of this study were 47 first grade children, 28 (59.57 %) boys and 19 (40.43 %) girls studying in the same school. Age ranged from 6 to 8 years (m = 6.77, SD = 0.4). The study included all of the children who were enrolled in two classes at the school. All children came from a middle-low SES.

Measures

A battery of literacy-related measures was administered in the middle of the first grade, pre-intervention, and at the end of the first grade, upon completion of the intervention program.

Early Literacy Measures

Phonological Awareness

1. Syllable Deletion (Shany & Ben-Dror, 1998) and Phoneme Deletion (Schwartz et al., 2006). These tests included three types of tasks (syllable, first phoneme, and last phoneme deletion) in which participants were required to delete a given syllable or phoneme from a spoken word in Hebrew. For example, “Say *mispar* (‘number’). Now, say *mispar* without *mis*”; each test list included ten words. In the phoneme deletion task the deletion resulted in the formation of nonwords.

In the syllable deletion test the deletion resulted in the formation of a word. The maximum possible score for each test was 10, internal consistency (alpha) for syllable deletion was 0.85, first phoneme deletion was 0.94, and last phoneme deletion was 0.93.

2. Letter recognition: In this test the child was presented with three printed letters on an otherwise blank sheet of paper (size A4). The child was asked to identify the letter that the examiner said orally. The test contained ten trails with three Hebrew letters in each, and the final score was the number of correct letters the child identified. The maximum possible score was 10. Internal consistency (alpha) was 0.64.

Word Reading and Fluency

Test of Word Reading Efficiency (TOWRE; Schiff, Kahta, & Katzir, 2006; adapted from Torgesen, Wagner, & Rashotte, 1999): The child was instructed to read aloud as many words as quickly as possible, in order to examine reading speed under timed conditions (45 s). The list contained 104 words ordered by increasing difficulty in the number of syllables, phonological structure, length, frequency, and morphological complexity. Scores ranged from 0 to 104, reflecting the number of accurate words the participant read in 45 s, with higher scores indicating higher reading speed.

Naming

1. Naming objects (Shatil, 1995): The child had to name, as fast as possible, 21 pictures of objects (such as house, dog, and tree). Each test had five different stimuli which were repeated several times, the total time of naming was measured as well as the number of errors in each test.
2. Naming letters (Shany, Lachman, Shalem, Bahat, & Zeiger, 2006): The child had to name, as fast as possible, 50 letters (such as ל,ג,ד,א,ס). Each test had five different stimuli which were repeated ten times, the total time of naming was measured as well as the number of errors in each test.

Procedure

The pre and post tests were individually administered over two sessions by trained Master's students in a quiet room at the school. Each session lasted approximately 20–30 min.

4 Results

First, in order to determine what the role of word reading fluency is, we report the descriptive statistics for the cognitive and literacy measures by the middle of first grade and by the end of first grade. Table 1 presents a summary of combined results from *t*-tests comparing literacy and cognitive skill from the middle of the first grade to the end of the first grade.

Overall, results demonstrate a statistically significant improvement in most of the measures from the middle of the first grade to measures that were assessed by the end of the first grade. In the measure of PA, however, there was an improvement in syllable deletion, but not in initial phoneme isolation. More importantly, the students improved markedly in word reading fluency. By the middle of first grade they read an average of about 7 words in 45 s and by the end of the year they read about 28 words within the same time frame, demonstrating the rapid growth of this skill during the first grade.

The next goal was to examine which components included in recent definitions of fluency (phonological awareness, rapid naming, vocabulary, etc.) are associated with word reading fluency by the middle of first grade and by the end of first grade. Tables 2 and 3 present the correlations between the measures in the middle of the first grade, and at the end of the first grade.

Table 1 Descriptive statistics and *t*-test results at the middle and at the end of first grade

	Middle of 1st grade		End of 1st grade		
Variables	Mean	SD	Mean	SD	*p*
RAN letters time	64.54	21.40	51.80	15.58	0.000**
RAN objects time	66.15	17.60	60.97	12.64	0.007**
Syllable deletion percent	23.96	24.75	71.26	26.83	0.000**
Initial phoneme isolation percent	61.36	31.59	62.00	34.94	0.711
TOWRE word reading	6.95	13.91	28.31	11.58	0.000**

TOWRE Test of Word Reading Efficiency (Torgesen et al.,1999), *RAN* Rapid Automatic Naming
*$p \leq 0.05$, ** $p \leq 0.01$

Table 2 Correlations between measures at the middle of first grade

Variables	1	2	3	4	5	6	7
1. TOWRE word reading	–						
2. Initial phoneme isolation	0.33*	0.51**	–				
3. Syllable deletion	0.67**	0.7**	0.57**	–			
4. RAN letter naming	–0.46**	–0.59**	–0.49**	–0.55**	–		
5. RAN object naming	–0.31*	–0.32*	–0.26	–0.48**	0.68**	–	

*$p \leq 0.05$, ** $p \leq 0.01$

Table 3 Correlations between measures at the end of Grade 1

Variables	1	2	3	4	5	6	7
1. TOWRE word reading	–						
2. Initial phoneme isolation	0.46**	0.6**					
3. Syllable deletion	0.57**	0.76**	0.49**				
4. RAN letter naming	–0.29	–0.23	–0.28	–0.17			
5. RAN object naming	–0.51**	–0.48**	–0.24	–0.33*	0.51**		

*p ≤ 0.05, ** p ≤ 0.01

Table 4 Stepwise regression results for word reading fluency at the middle of first grade

Predictors		R	R^2	ΔR^2	ΔF
	Syllable deletion	0.67	0.44	0.44	24.37*

*p ≤ 0.00

Table 5 Stepwise regression results for word reading fluency at the end of Grade 1

Predictors		R	R^2	ΔR^2	ΔF
	Syllable deletion	0.57	0.33	0.33	21.37*
	RAN Object naming, time, (in s)	0.66	0.44	0.11	8.82*

*p ≤ 0.01

As shown in these tables, word reading fluency in the middle of Grade 1 was correlated with all measures. At the end of Grade 1, word reading fluency was also correlated with all other measures, but with RAN letter naming.

The third research question examined what skills from the middle of the first grade predict word reading fluency at the same point in time. To answer the following question, stepwise multiple regressions were carried out. Results are presented in Table 4.

Table 4 demonstrated that syllable deletion as measured by the middle of grade 1 explained 44 % ($p < 0.01$) of the word reading fluency variance measured at the middle of first grade.

Our next goal was to examine what measures predict word reading fluency at the end of the first grade. Table 5 presents a regression model to determine the variance contributed to word reading fluency measures at the end of the year.

Syllable deletion measured at the end of the first grade explained 33.0 % of the variance ($p < 0.01$); and RAN at the end of the first grade added to the explanation an additional 11 % of the variance ($p < 0.01$). Taking it all together, syllable and RAN explain 44 % of the word reading fluency variance measured at the end of first grade.

In summary, our first research question examined what the development of word reading fluency is in Hebrew during the first grade. Our preliminary results demonstrate that in Hebrew orthography, there is a rapid growth in word reading fluency during the first grade. Lower level components such as phonological awareness predicts word reading fluency at the middle of first grade and that syllable deletion and RAN predicts word reading fluency at the end of first grade.

5 Discussion

In this chapter, we suggest a preliminary model of the development of early reading fluency in first grade Hebrew speaking children. The case of Hebrew as a transparent orthography is interesting in order to understand the processes that are involved at the very beginning of reading acquisition. The results demonstrated that in Hebrew orthography, there is a rapid growth in word reading fluency during the first grade. Syllable deletion predicts word reading fluency at the middle of first grade. By the end of first grade, two skills predict word reading fluency: RAN and syllable deletion.

Our study is one of the first longitudinal studies of the Hebrew orthography in the first grade that examined word reading fluency. As in other transparent orthographies, we found that first grade literacy skills developed rapidly for most children. The transition from reading accuracy to reading fluency (Chall, 1983) in Hebrew, is especially rapid due to the transparent nature of the orthography at that stage, and occurs not towards the end of second grade but has its first indicators by mid first grade, with a rapid growth from the middle to end of the first grade.

The second goal of the study was to examine the relationships between word reading and cognitive skills as were measured by the middle and by the end of the first grade. Results of this study demonstrate that the construct of word reading fluency is complicated and provide support to a more broad definition of fluency that takes into consideration skills such as PA, RAN and more. Future research should examine additional linguistic and cognitive skills (such as visual perception and attention) in relation to word reading fluency.

Overall, results demonstrate that phonological awareness was a significant variable that predicted reading fluency at the middle and at the end of the first grade. The results are consistent with previous studies that examined Hebrew-speaking learners at higher grades that found that phonological awareness plays an important role in word reading fluency (Ziegler et al., 2010; Katzir et al., 2012). It is interesting to note that syllable deletion by the middle and by the end of the first grade was the only phonological awareness skill that predicted word reading fluency in the first grade. It might be the case that because Hebrew is a syllabic language, the ability to manipulate words in the syllable level contributes to the fluency at that stage because this skill is being mastered.

Not surprisingly, RAN was found to be another variable that contributed to word reading fluency in the first grade. This finding is consistent with many other studies demonstrating the contribution of RAN to fluent reading (Kim, Park, & Lombardino, 2015; Pennington, Cardoso-Martins, Green, & Lefly, 2001; Katzir et al., 2006).

The current study examined the development of word reading fluency at two points in the first grade. The study demonstrated that word fluency in this grade changes rapidly and as such, needs close monitoring developmentally. Our study demonstrated that one variable, syllable deletion, by the middle of first grade, explained 44 % of word reading fluency. By the end of first grade, two variables, RAN and syllable deletion, explained 44 % of word reading fluency. The change in reading fluency from the middle to the end of the year in first grade, as was observed by the *t*-test comparison, calls attention to the pedagogical need to monitor this skill in Hebrew and emphasizes the need to include fluency theoretically in models of reading as well as in related practice of early reading development in Hebrew.

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Part II
Intervention

A Fact Retrieval Account of the Acceleration Phenomenon

Telse Nagler, Sven Lindberg, and Marcus Hasselhorn

Abstract Breznitz (J Educ Psychol 89:289–297, 1987a; Fluency in reading: synchronization of processes. Erlbaum, Mahwah, 2006) demonstrated that a fading manipulation, which continuously erases text based on the individual reading rate, results in improved reading performance. Several studies using this fading procedure showed that children as well as adults with different reading proficiency levels and in different languages were able to increase their reading rate and reading comprehension in a fading condition, characterizing the Acceleration Phenomenon. Considering the close interconnection of reading fluency and reading comprehension, a fact retrieval account for achievement enhancements induced by the fading manipulation is presented in this chapter. It is hypothesized, that if information can be processed at a high level of automaticity and available lexical entries can be accessed rapidly, reading performance can be improved by means of imposing a time limitation. Hence, the nature of the fading manipulation may induce a shift to faster and more elaborated strategies, such as direct fact retrieval, resulting in improved performance. Different empirical outcomes from the reading and the arithmetic domain are demonstrated and the generalizability of the Acceleration Phenomenon across academic domains is discussed.

Keywords Reading fluency • Intervention • Training • Reading acceleration • Acceleration phenomenon • Reading-disability

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1 Introduction

To build and develop reading proficiency is one of the major curriculum goals in elementary school education (Gough, Hoover, & Peterson, 1996; Stanovich, 1991). Relevant prerequisites for reading skill acquisition range from fundamental cognitive factors such as word decoding (Compton et al., 2005) to higher-level factors such as reading comprehension (Wolf & Katzir-Cohen, 2001). Generally, the main goal in reading acquisition is to gain access to meaning. Before script can be comprehended, however, letters need to be deciphered and recognized as words. The code, which represents speech as a sequence of visual symbols, needs to be acquired and internalized. In early reading acquisition, children therefore need to master the symbol-to-sound translation, the so-called *phonological recoding* (Share, 1995). If letters (graphemes) are successfully mapped to their correct sounds (phonemes), strings of letters can be deciphered. After this initial recoding phase and through practice, the knowledge about orthographic characteristics of words develops. Beginning readers start to form lexical entries in their mental lexicon, which include specific information about a word's orthographic structure, resulting in the recognition of specific letter sequences belonging to a specific word (Shaywitz & Shaywitz, 2005). This *orthographic knowledge* refers to the knowledge an individual has of the spelling, conventions and rules regarding the letter sequences and positions within a word (Corcos & Willows, 1993). Correctly decoded words can subsequently be stored as orthographic representations (Thaler, Ebner, Wimmer, & Landerl, 2004) and the relationships between orthography and its phonological forms can be connected to morphological and lexical-semantic information (Pugh et al., 2001). Once words can be identified with high accuracy, rapid processing is possible (Ehri & Wilce, 1983) as a word's meaning can be retrieved directly from lexical memory. Automaticity and reading fluency are thus associated with accurate and quick reading of connected text and with proficient reading comprehension (Kuhn & Stahl, 2003). One of the most important outcome measures linked to reading fluency is the reading rate, which is associated with the speed of processing (Meyer, Talbot, & Florencio, 1999). According to research findings, the reading rate can also function as a manipulable independent variable (Breznitz & Berman, 2003). An emerging line of research demonstrated a counter-intuitive finding: Improvements in reading speed and reading comprehension were inducible by using an artificial text fading procedure, erasing presented text in reading direction according to the individual fastest reading speed (Breznitz, 1987a). This pattern of results is known as the Acceleration Phenomenon. Focusing on reading fluency and reading comprehension as a basis of Breznitz' work, the present chapter addresses several issues regarding the Acceleration Phenomenon and its underlying processes.

2 Reading Fluency

According to Wolf and Katzir-Cohen (2001), reading fluency refers to "a level of accuracy and rate where decoding is relatively effortless; where oral reading is smooth and accurate with correct prosody; and where attention can be allocated to comprehension" (p. 219). This definition pictures the complexity of reading fluency and the interdependency of phonological, orthographic and semantic processes, accuracy and speed. Obviously, only accurate and efficiently working decoding processes can result in reading fluency. Established theories such as most information processing models focus on the description of underlying processes that are important for reading fluency. According to the *model of automaticity* proposed by LaBerge and Samuels (1974), exposure and practice will lead to a perception of single elements of script (e.g., letters) as units. As more and more units can be accumulated and decoding increasingly becomes automatic, attention paid to early visual coding processes (i.e., symbol recognition) decreases. Instead, attention can be reallocated, and cognitive resources can be shifted from lower-level processes such as decoding, to higher-level processes such as extracting meaning from text. In Perfetti's (1985) *verbal efficiency theory*, reading fluency is referred to as 'effective reading speed', which is characterized by comprehension accuracy (i.e., correct understanding of semantic content) and high reading rates. Perfetti's model focuses on individual differences in reading comprehension and includes the (efficient) operation of orthographic, phonological as well as semantic processes. One central component of Perfetti's model refers to the notion that the construction of mental representations is of great importance for reading fluency. Perfetti emphasizes that the quality of mental representations is likely to affect the further development of efficiency, as the ease of lexical retrieval supposedly depends on the quality of representation. Accordingly, working memory functioning would be positively influenced by high-quality mental representations, as these would be retrieved faster from the mental lexicon, allowing the release of capacity and the focus on higher-level demands, such as reading comprehension.

3 Reading Comprehension

Rost and Schilling (2006) defined reading comprehension as the competence to extract meaning from written text. The relationship between reading fluency and reading comprehension has been outlined as most relevant for successful reading performance (Huemer, Landerl, Aro, & Lyytinen, 2008). High speed of processing is assumed to be fundamental for proceeding to the next stage in reading development, namely proficient reading comprehension (Leinonen et al., 2001). Only fluent reading performance allows for automatized extraction of semantic information from text and engagement in direct fact retrieval. It is hardly surprising that moderate to high positive correlations were found in empirical studies investigating the relationship between reading comprehension and reading fluency (Huemer et al., 2008; Klauda & Guthrie, 2008). Thus, it is proposed that automatic and efficient processing eventually strengthens the paths to available long-term memory content so that meaning can be directly retrieved from text, resulting in high reading comprehension (Woltz & Was, 2006, 2007). This assumption is supported by empirical evidence showing that increasing reading fluency also results in higher reading comprehension achievement (Huemer et al., 2008).

4 The Acceleration Phenomenon

As outlined above, empirical evidence strongly suggests that with increasing reading fluency, reading comprehension can be enhanced (Huemer et al., 2008; Kuhn & Stahl, 2003). Hence, various studies have placed a focus of interest on the experimental investigation of reading fluency, most often measured as reading rate (i.e., number of words or letters read per time unit; Carver, 1991, 1997; Meyer et al., 1999). One line of research suggested to consider individual reading rate not only as a dependent (outcome) variable but also as an independent variable that can be manipulated experimentally (Breznitz & Berman, 2003). Findings in this research field revealed the Acceleration Phenomenon: Breznitz (1987a) reported the counter-intuitive finding that participants who are artificially pushed to read at a faster reading rate show better results in reading performance regarding reading rate, reading accuracy and reading comprehension, compared to their self-paced reading achievement. The Acceleration Phenomenon has been investigated in various studies (for a review, see Breznitz, 2006) in children and adults (Breznitz, 1987a; Breznitz & Leikin, 2001) as well as in different languages and writing systems (Hebrew, English, German; Breznitz, 1997a, 1997b; Nagler, 2012; Nagler, Linkersdörfer, Lonnemann, Hasselhorn, & Lindberg, 2016).

The typical Acceleration Phenomenon paradigm used to examine the effects of the artificially increased reading rate on reading performance is based on a three-block design. In the first condition (self-paced 1) computerized items (i.e., sentences) are presented to each participant. Participants are asked to read the reading material at their individual routine reading rate. The needed reading time is measured individually. Multiple-choice questions follow for comprehension measurement and decoding errors are registered as a measure for reading accuracy. During the second condition (fading), additional parallel forms of sentences are subsequently presented to each participant using a computerized text erasing procedure. Through this procedure, text is faded out continuously in reading direction, usually at the fastest measured reading rate determined in the self-paced 1 condition. Reading rate, decoding accuracy and reading comprehension are again measured and recorded. In the third condition (self-paced 2) the participants once again read text at their normal reading rate, comparable to the procedure of the first self-paced condition. Subsequently, reading performance is compared between conditions. The characteristic trait of the Acceleration Phenomenon is that participants enhance their reading performance in the fading condition, but relapse during the self-paced 2 condition to their initial reading rate as determined in the first self-paced condition. The Acceleration Phenomenon is therefore a momentary phenomenon, observable in cross-sectional experimental designs only in the fading condition.

Interestingly, data from Acceleration Phenomenon studies have reported a relatively greater improvement of reading performance enhancement for disadvantaged participants (Breznitz, 1987b); data suggested that reading in the fading condition seems to particularly foster the reading performance of readers with problematic reading achievement. Several studies (Breznitz, 1997a, 1997b; Breznitz & Leikin, 2001) reported a significantly greater decrease in decoding errors as well as an increase in reading rate and comprehension for dyslexic samples compared to normally achieving participants.

Considering the manifold empirical evidence, the question of what underlying factors may trigger the reading performance enhancements in the accelerated fading condition has been of central relevance in the history of Acceleration Phenomenon research. Four major assumptions regarding the origin of Acceleration Phenomenon effects have been proposed:

1. *The attention approach*. It seems plausible that the fading procedure may foster the individual's attention. If an individual successfully concentrates his/her attention on the reading process itself, the reading performance is likely to be enhanced (Walczyk, Kelly, Meche, & Braud, 1999). In this regard, text fading is considered to induce reduced distractibility and to increase the focus on the reading task. To test this assumption, reading tasks utilizing pictorial distractors above presented text were introduced in an empirical study (Breznitz, 1988). Participants were asked to ignore the distractors while reading. To examine whether participating first graders would direct more attention to the reading material if text was faded out, one group of participants read text with text fading and another group without (i.e., control group). Results indicated that participants in the fading group recalled statistically significantly fewer distractors than the readers in the control group. Hence, it was assumed that the shift of attention and the reduced distractibility resulted in improved reading comprehension (Breznitz, 1988; Breznitz & Share, 1992).
2. *The decoding approach*. The second explanatory approach refers to the processing of reading material, which is especially relevant for individuals with reading difficulties. The fading procedure might produce a processing shift from the sequential and slow phonological route to the more direct orthographical (visual) route. Breznitz (1997b) investigated reading performance in self-paced and fading conditions, inducing an auditory masking manipulation (i.e., a well-known children's song). Results indicated that participants improved their reading rate during the fading condition compared to their self-paced reading performance. Comparably, the introduced auditory masking enhanced reading performance in the self-paced reading condition. As especially phonological decoding seems to be problematic for dyslexic children, it was assumed that the interference in the auditory channel through the children's song might have encouraged the children to rely more on alternative information processing. More precisely, Breznitz suggested that the children may have become more engaged with less impaired orthographic decoding when exposed to auditory distractors. As the children

showed comparable reading improvements in the acceleration condition, it was assumed that the effect of the fading procedure might also shift the emphasis from phonological decoding to other routes of information processing, such as orthographic decoding, resulting in more efficient processing of information.

3. *The working memory approach*. A third assumption is that short-term memory capacity can be relieved due to reading acceleration resulting in a working memory optimization. Breznitz and Share (1992) tested the influence of computerized acceleration on different working memory tasks. In a first working memory task, the participants were asked to repeat each presented sentence in backward and forward order. A second task contained reading material with changes in semantics or wording. Following a target passage, two test passages were simultaneously presented, showing the original and an altered version of the passage. The participants were asked to identify the original passage. In a third task, participants were confronted with a single word (probe) after reading a passage and were asked to recall the words which had appeared immediately before and after the probe. The results revealed significantly faster reading rates and better performance for all working memory tasks in the fading condition compared to the self-paced reading condition. The authors assumed that a significant gain of working memory capacity may have resulted in enhanced performance in the working memory tasks in the accelerated fading condition.
4. *The fact retrieval approach*. Finally, in a fourth explanatory approach, the effects observable in Acceleration Phenomenon studies were attributed to an increase in direct word retrieval from the reader's mental lexicon. To test this assumption, Breznitz (1987a) presented word material that deliberately included orthographic mistakes to assess children's correction behavior. Results indicated that the participants self-corrected almost twice as many errors in the fading condition as in the self-paced condition. Simultaneously, the comprehension scores increased in the fading condition compared to self-paced reading achievement. The interpretation was offered that due to the fading procedure and the induced faster reading rates, words are recognized at once and their semantic meaning is more often directly retrieved from lexical memory.

Taken together, substantial evidence has been collected in previous Acceleration Phenomenon studies, robustly documenting enhancements regarding faster reading rates and enhanced reading comprehension. Furthermore, a number of explanatory approaches to the Acceleration Phenomenon effects have been postulated and substantiated by empirical evidence. However, it is not yet clear which underlying processes may be most influential for the Acceleration Phenomenon effects.

5 Seeking Further Evidence for the Fact Retrieval Account

With regard to information processing models, attention allocation and decoding processes are necessary to gain automaticity. However, cognitive capacity can only be relieved if high-quality mental representations are established (Perfetti, 1985).

Consequently, with strengthened paths to available long-term memory content, meaning can be directly retrieved from text, resulting in elaborated reading comprehension (Woltz & Was, 2006, 2007). With these assumptions in mind, the fact retrieval approach seems to be central for reading enhancement in Acceleration Phenomenon research. Hence, for further clarification of underlying processes accountable for Acceleration Phenomenon effects, we systematically pursued the adequacy of the fact retrieval account on the bases of our own empirical data.

6 Influence of Reading Material Characteristics

Reading comprehension seems to be mainly influenced by internal cognitive processing, specifically by the existence of high-quality mental representations and the fast retrieval of semantic information. However, external factors such as the characteristics of reading material can also affect comprehension achievement. Hiebert and Fisher (2010) addressed three influencing characteristics affecting information processing: (1) the number of syllables per word, (2) the number of words per sentence, and (3) the words' frequency. The number of syllables per word is a central issue for word identification. In this regard, Hoover and Gough (1990) assumed that reading comprehension is dependent on decoding efficiency. Accordingly, lower-level decoding processes, such as letter-to-sound correspondence, are accountable for high or low reading comprehension, as words are more or less successfully identified. Consequently comprehension is affected by problematic word identification. Moreover, research suggests that the more syllables there are in a word, the longer it takes to be processed (Baddeley, Thomson, & Buchanan, 1975). Words with few syllables are hence decoded and recalled more easily than words with many syllables (McNerney, Goodwin, & Radvansky, 2011). Furthermore, the number of words per sentence influences reading comprehension. Research concentrating on working memory capacity and reading reported that recall was more often correct for items with a small number of words than for items comprising many words (Goldman, Hogaboam, Bell, & Perfetti, 1980).

What is most interesting for the fact retrieval account pursued here is that some studies found highly frequent words to be recognized faster and more accurately than less frequent words (Balota & Chumbley, 1984; Walczyk et al., 2007). This *word frequency effect* is well documented and was observable in behavioral (e.g., Gollan, Slattery, Van Assche, Duyck, & Rayner, 2011), eye-tracking (e.g., Dürrwächter, Sokolov, Reinhard, Klosinski, & Trauzettel-Klosinski, 2010; Hutzler & Wimmer, 2004; Hyönä & Olson, 1995), electroencephalography (e.g., Hauk & Pulvermüller, 2004; Rabovsky, Álvarez, Hohlfeld, & Sommer, 2008) and functional imaging studies (e.g., Kronbichler et al., 2004). An attempt to explain the *word frequency effect* assumes that mental representations are better connected for frequent words because frequency of activation results in better connections between the mental representations forming high-quality lexical entries (Seidenberg & McClelland, 1989). Lexical access is therefore assumed to be frequency-sensitive and lexical entries for highly frequent words are supposed to be more available for identification than are lexical entries for less frequent words.

Based on the hypothesis that lexical entries for high-frequency words are more readily accessible for identification than lexical entries for low-frequency words, as demonstrated by previous research (Forster, 1976; Seidenberg & McClelland, 1989), we assumed that reading material with different characteristics would be processed in different ways. Hence, in an empirical study three characteristics (i.e., number of syllables, number of words per sentence, word frequency) were consolidated, introducing the term of *lexical accessibility* (LA) to differentiate reading material with different preconditions for efficient and automatized processing (Nagler, Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2014). Reading material with three different levels of LA (easy, intermediate, difficult) was generated to investigate reading performance when processing different reading materials with and without fading manipulation. Reading material with an easy level of LA thereby comprised well readable material including frequent words and was considered to be easily processed. The reading material at the intermediate and difficult levels of LA, on the other hand, was considered to be increasingly more demanding due to reduced readability and low frequency of words. The reading material (i.e., sentence, questions and four multiple-choice answer options) with different levels of LA was presented to a sample of 39 third-grade readers in an Acceleration Phenomenon setting (i.e., three conditions: self-paced 1 – fading – self-paced 2), comparing reading rate and reading comprehension across conditions and LA levels. Data revealed that for all LA levels, children's reading rates increased significantly due to text fading. However, reading comprehension was sensitive to the text materials' characteristics. Reading comprehension enhancements were observable for easily accessible reading material but not for material with intermediate or difficult levels of LA. Material that was difficult to retrieve from the mental lexicon even resulted in reduced reading comprehension in the fading condition.

The results encourage us to further pursue the fact retrieval account, assuming that direct fact retrieval may be affected differently depending on the reading materials levels of LA. Generally, there are more or less elaborated strategies to approach a task which differ in effectiveness and processing time, the most effective and fastest strategy being direct fact retrieval (Siegler, 1991). In the described study, material with easy LA had all the prerequisites to be directly retrieved from the mental lexicon and to be automatically processed as it consisted of highly frequent words and was well readable. Most children show well-established associative paths to the mental lexicon for frequent words (Farrington-Flint, Coyne, Stiller, & Heath, 2008; Lindberg et al., 2011). Hence, it seems that the existing paths for frequent words might have been used even more successfully in the fading condition than during self-paced reading conditions, resulting in faster reading rates and better reading comprehension for reading materials with easy LA level. Reading items with difficult LA level, on the other hand, produced opposite effects. Although the reading rate was increased due to the fading procedure, participants showed more comprehension errors compared to their self-paced reading performance when processing reading material with a difficult level of LA. Since materials with a low or difficult level of LA comprised low-frequency words and was more demanding, processing was assumedly challenging in the fading condition. Hence, it seems possible that direct fact retrieval may not have been frequently used for material with a difficult level of LA and did therefore not affect reading comprehension positively. On the contrary, cognitive capacity may have even been overstrained by the limitation of processing time when processing challenging material in the fading condition. However, reading rate even improved for challenging materials with intermediate and difficult levels of LA. It is therefore suggested that a shift from less to more elaborated backup strategies (e.g., from letter-by-letter to syllable-by-syllable decoding) might have been achieved, resulting in faster reading rates without positively affecting reading comprehension.

7 Acceleration in the Domain of Arithmetic

The reading domain may not be best suited to gain more precise information about possible strategy usage and the influence of fact retrieval on Acceleration Phenomenon effects. One sentence may contain words which can be retrieved directly from the mental lexicon as well as words which need to be decoded using less elaborated backup strategies, such as merging syllables or parts of words. Hence, although reading material can be classified into more or less difficult (i.e., different levels of LA), the probability of strategy usage is most likely mixed, rendering it difficult to gain exact information about strategy behavior when investigating reading tasks. In other domains like arithmetic, it is much easier to differentiate tasks with respect to the strategy typically applied to solve a problem. Certainly, arithmetic problems can be solved either by retrieving the outcome directly from long-term memory (i.e., retrieval strategy), or by more time-consuming procedural strategies, such as counting or decomposing (e.g., $9+6=10+6-1=15$). More precisely, in early arithmetic knowledge acquisition, procedural strategy usage outnumbers the use of fact retrieval strategies. In the course of development and with increased fluency and expertise, procedural strategies are gradually replaced by frequent direct fact retrieval (Campbell & Xue, 2001), although both strategies are continuously used into adulthood (De Smedt, Holloway, & Ansari, 2011). However, the reliance on procedural-related or retrieval-related strategies varies according to the task and according to the arithmetic operation performed. Multiplication tasks, for example, are likely to be solved with retrieval strategies. Multiplication tables are considered over-learned arithmetic facts, which are stored in verbal memory as they are typically learned by memorization. Addition tasks can be solved in at least two ways. Similar to multiplication, some basic addition problems (single digit addition with a sum ≤ 10) are often memorized and can be directly retrieved from the mental lexicon. However, more advanced addition tasks with large operands (with a sum >10) are usually not processed by rote and are generally solved by various procedural strategies (Dehaene & Cohen, 1995; LeFevre, Sadesky, & Bisanz, 1996). Taken together, simple addition and multiplication tasks are generally solved by direct fact retrieval whereas advanced addition tasks are mainly solved by procedural strategies (Campbell & Xue, 2001; De Smedt et al., 2011). Hence, arithmetic tasks may provide additional valuable insights into the application of fact retrieval strategies.

We assumed that the use of retrieval-related multiplication tasks and procedural-related advanced addition tasks in an acceleration phenomenon setting (i.e., three conditions: self-paced 1 – fading – self-paced 2) would enable a direct comparison of the effects of different strategy usages. Therefore, the Acceleration Phenomenon paradigm was applied to a new cognitive domain, namely the field of arithmetic. Tasks were presented in an acceleration setting to compare calculating behavior when solving arithmetic problems with and without fading (Lindberg & Nagler, 2011). If the assumption that Acceleration Phenomenon effects are mainly attributable to improved fact retrieval is true, facilitation of fact retrieval should be particularly well observable when using retrieval-related multiplication tasks. We thus hypothesized that children's calculating speed and calculating accuracy would improve during the arithmetic-fading manipulation for multiplication tasks due to an increased use of direct fact retrieval. On the other hand, no effects were expected while solving advanced addition tasks, as it was suggested that procedural strategies would not profit from the arithmetic-fading manipulation.

Eighty-five third graders participated in the experiment. For the arithmetic-fading paradigm, mental arithmetic tasks were used that are typical for the third grade elementary school curriculum. The pool of tasks consisted of multiplication and advanced addition problems with two operands. The sum of the advanced addition operands always exceeded 10 (e.g., $8+13$ or 7×6). The individual calculating time needed for each arithmetic task and the calculation accuracy were determined. The recorded calculating time in the self-paced 1 condition was used to define the fading speed for the items in the fading condition. The fading procedure was adapted to arithmetic processing, using a holistic fading procedure (i.e., the complete arithmetic task became less visible until it disappeared). Results revealed that calculation errors declined and processing time decreased significantly in the fading condition for multiplication tasks, whereas no effects were found for addition tasks. The faster calculating speed seemed to further positively influence the accuracy of calculating outcomes. Results indicated that children solved more multiplication problems correctly in the fading condition as compared to their self-paced calculating performance. Advanced addition problems were solved equally across all conditions. Hence, while procedural-related advanced addition tasks were not affected by the fading manipulation, the performance of retrieval-related multiplication tasks was enhanced with regard to calculation speed and calculation accuracy.

The results and the direct comparison of procedural- and retrieval-related arithmetic tasks provide valuable information about the underlying processes that might be relevant to induce Acceleration Phenomenon effects. The findings support the interpretation that the fading procedure enhances the retrieval of arithmetic facts from the mental lexicon, as only retrieval-related tasks were solved more effectively in the fading condition.

8 Discussion

Given the presented empirical data, it was suggested that improved rate and comprehension (i.e., Acceleration Phenomenon effects) are only observable if the material meets the prerequisites for direct retrieval from an individual's mental lexicon or long-term memory. This conclusion emerged from the findings that (1) participants only showed reading rate and reading comprehension gains in the fading condition when processing material that is considered to be easy to retrieve from the mental lexicon, and (2) only retrieval-related multiplication tasks, but not procedural-related addition tasks, were solved faster and more accurately through the fading manipulation. However, challenging material, such as reading material with intermediate or difficult LA level, was also processed faster in the fading condition than in the self-paced condition. Hence, further considerations are needed to fully explain the processes and mechanisms surrounding the Acceleration Phenomenon.

9 Theoretical Elaboration of the Fact Retrieval Account

To add a new theoretical account to the fact retrieval approach to explain Acceleration Phenomenon effects, it seems helpful to outline how children solve specific tasks. Many alternative strategies are available which are applied in different ways. The *overlapping waves model* (Siegler, 1996) proposes that there is more than one strategy to approach a particular problem and that strategy application is characterized by variability, adaptive choice and gradual change over time. Hence, different strategies can coexist and persist in the course of development. The choice of strategy to solve a task can vary between individuals as well as within an individual. Overall, children use a variety of strategies to solve a single problem, which differ in their effectiveness and processing time. Direct fact retrieval is considered to be the fastest and most efficient strategy, while less elaborated backup strategies (e.g., counting or letter-by-letter decoding) are more time-consuming and tend to be more error-prone. Strategy use differs depending on the task and the situation. Easy or familiar tasks, for example, are often solved by effective and fast retrieval of information (Siegler, 1986). For instance, highly frequent words are retrieved more often from the mental lexicon than infrequent words (Balota & Chumbley, 1984; Walczyk et al., 2007) because their paths to lexical memory are well-established and facilitate direct access. Retrieval-related strategies, however, cannot always be applied as they require high-quality representations and immediate access to stored information. Infrequent words or advanced addition tasks, for example, usually exhibit no or only unstable paths to the individual's lexical memory, hence more effortful backup strategies are applied (Lindberg et al., 2011). An explanation of the likely choice of strategy for solving a task is given by the *distributions of associations' model* (Siegler, 1986): Originally developed in the field of arithmetic (Rittle-Johnson & Siegler, 1999; Siegler, 2005), it is assumed in the model that the usage of a specific strategy is determined by associations with differing strengths, different search lengths and an individual confidence criterion which needs to be exceeded in order to address the association. To give an example, if a relatively easy task is solved (*2+1*), the association to the right outcome (=*3*) might be very strong. Hence, the individual confidence criterion can be promptly exceeded and the outcome can be directly retrieved. However, if the task is more demanding (*16+8*) the association to the right outcome (=*24*) may be not as strong and there may be more than one association (*23*, *24*, *25*). In this case, the confidence criterion might not be immediately exceeded as all associations are considered and the search length is extended, resulting in less efficient processing and possibly in more error-prone outcomes. However, it has been demonstrated that even though fact retrieval may be possible for certain tasks, children often rather rely on less elaborative backup strategies (Lindberg et al., 2011; Lindberg, Linkersdörfer, Lehmann, Hasselhorn, & Lonnemann, 2013).

Against the background of theoretical considerations regarding strategy behavior, the empirical results presented in this chapter can be interpreted. We assume that the nature of the fading manipulation induces a subjective feeling of time constraint as the processing time is limited through the erasing of text or arithmetic tasks. Information is only available for a given time frame, resulting in a restricted search length. Consequently, the strategy chosen to solve a task should be fast and efficient to process all information before it disappears. Hence, the fading manipulation might evoke a shift from less elaborate to more elaborate strategies, such as fact retrieval, more frequently. However, referring to the *distributions of associations*' *model* (Siegler, 1986), the probability of exceeding the individual confidence criteria might differ depending on task characteristics. If the task meets the prerequisites to be solved by direct fact retrieval (i.e., reading material with easy LA or multiplication tasks), the fading manipulation most likely supports engagement in direct fact retrieval rather than dependence on less elaborated backup strategies, resulting in enhanced speed and comprehension. If the prerequisites for a direct association to the right outcome are not frequently given as the paths are unstable or non-existent, less elaborated strategies need to be chosen to solve the task. With regard to the effectiveness of the fading manipulation, however, it is assumed that even though the shift to direct fact retrieval may not be feasible for challenging tasks, a shift from less to more elaborated backup strategies could be achieved none the less, resulting in faster processing performance.

10 Generalizability of Acceleration Phenomenon Effects

Finally, the question arises to which extent Acceleration Phenomenon effects found in the field of arithmetic and the field of reading are comparable. Obviously, both operations differ in the way tasks are presented. Reading tasks are sequentially decoded (i.e., in German from left to right) and comprise strings of letters representing words with meaning. Calculation tasks are perceived more holistically and comprise numbers and several signs determining which operation needs to be performed (i.e., addition, subtraction, multiplication or division). However, research has suggested that reading and arithmetic involve very similar cognitive demands (Lundberg & Sterner, 2006). Specifically attention (Fuchs et al., 2006), phonological decoding (Bull & Johnston, 1997; Geary, 1993), working memory (Gathercole, Alloway, Willis, & Adams, 2006; Geary, Hoard, Byrd-Craven, & DeSoto, 2004), and processing speed (Ramos-Christian, Schleser, & Varn, 2008) are suggested to be required for successful arithmetic achievement. Particularly language-based skills seem to be crucial for both domains. Phonological processes for example are not only critical for reading, but may also be important for temporary storage of digits in working memory. Phonological decoding is fundamental for verbal counting strategies as well as for arithmetic fact learning, such as memorizing (Durand, Hulme, Larkin, & Snowling, 2005). Working memory is important to temporarily store information while performing mental operations, such as adding or subtracting numerals (Berg, 2008). Arithmetic processing speed, or fluency, has been outlined not only as a factor for highly accurate calculating achievement (Therrien, 2004), but also as an indicator for successful transfer of arithmetic principles to new domains (Binder, 1996) and crucial for successful problem solving (Ramos-Christian et al., 2008). Moreover, research has suggested that numerals can be represented in a verbal-phonological code (Dehaene, 1992; Dehaene & Cohen, 1995). This assumption has received support from neuroimaging data, revealing a neuronal overlap between phonological processing and arithmetic fact retrieval in the left-temporo-parietal junction (Dehaene, Piazza, Pinel, & Cohen, 2003; Grabner et al., 2009; Pugh et al., 2001).

Because of the accordance of relevant factors for the arithmetic domain as well as the reading domain, we draw the conclusion that the processes accountable for Acceleration Phenomenon effects are the same in reading as well as in arithmetic tasks. Therefore, it can be argued that Acceleration Phenomenon effects examined with reading materials and with arithmetic tasks most likely reflect the same phenomenon.

11 Conclusion

The presented findings provide evidence that the Acceleration Phenomenon might be a general phenomenon across cognitive domains as Acceleration Phenomenon effects are observable not only in reading but also in arithmetic tasks. Furthermore, the empirical data and theoretical discussion propose that Acceleration Phenomenon effects evolve from a shift from less to more elaborated strategies, presumably to a more frequent usage of fact retrieval. If processed materials' prerequisites do allow for direct fact retrieval, information is most likely retrieved directly from the mental lexicon due to the time limitation given by the fading manipulation, positively affecting speed and comprehension performance. Challenging tasks, however, may be less frequently solved via highly elaborated strategies. In this case, procedural strategies have to be applied which are naturally more effortful. Nonetheless, the fading manipulation may induce a shift from less to more elaborated backup strategies resulting in faster speed of processing and facilitating a more elaborated strategy behavior within the boundaries of feasibility. In future research, the analysis of children's strategy behavior should be integrated in Acceleration Phenomenon studies to help explain emerging Acceleration Phenomenon effects in more detail.

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Training Reading Skills in Finnish: From Reading Acquisition to Fluency and Comprehension

Mikko Aro and Heikki Lyytinen

Abstract This chapter outlines the approaches for supporting reading development in Finnish that have been developed on the basis of current knowledge on reading development and reading disabilities in Finnish. We discuss also the challenges that the features of Finnish language and orthography pose for the reader at various points of development. We also describe the means for supporting the acquisition of the earliest milestones in reading development, that are being used widely within the Finnish elementary schools, and that have been based on findings of a large longitudinal research project (Jyväskylä Longitudinal Study of Dyslexia, JLD). Although the knowledge on the development of reading fluency is still scarce, we outline also the research approaches aiming at developing efficient means for supporting readers struggling with fluency development, as well as aims for supporting reading comprehension using IT-based tools.

Keywords Reading acquisition in Finnish • Finnish orthography • GraphoGame • Reading fluency training • Reading comprehension

1 Introduction

The research on reading disabilities in Finland has been characterized from early on by an emphasis on applied research. The early focus of reading and reading disabilities research was on assessing and developing means of identification of and support for children with reading disabilities. This is related to the fact that the research on reading disabilities was carried out within research groups with close ties to clinical work, and the research questions were related to practical issues relevant for practitioners in schools and clinical settings. For the same reason, the research was

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often carried out in multidisciplinary groups combining expertise from a number of disciplines.

More basic aspects of reading development and reading disabilities were, however, less studied before the Jyväskylä Longitudinal Study of Dyslexia (JLD) (see Lyytinen et al., 2008). JLD was initiated in the early 1990s, and the ambitious aim of the project was to investigate the developmental course of typical and impaired literacy development with a follow-up starting very early and continuing up to school age. The participating families were recruited in maternity clinics and the follow-up started already from birth with two groups of participating children: Those with a strong familial background of reading disabilities, and those with no familial history of reading disabilities. Inclusion based on familial background was on the one hand a methodological decision from the point of view of sampling; due to heredity, the incidence of actual reading disabilities would be higher in a group of children with a family history of reading problems. On the other hand, it opened up possibilities to investigate both genetic and familial effects on literacy development. Although one central aim of JLD was basic research of cognitive and language development and their relation to later literacy development, the project has very explicitly aimed at finding the very early indicators of problems in language and literacy development, as well as means of successful intervention and support of literacy development. Parallel with JLD, other simultaneous projects have also contributed to the knowledge base of literacy development in Finnish. Multidisciplinary orientation and interest in practical application of findings also characterize JLD. The study has covered a wide field of research questions related to developmental psychology, brain research, linguistics, genetics, and education.

JLD and the projects related to it have contributed markedly to the empirical foundation for literacy acquisition in Finnish and more generally, provide information about factors that may compromise becoming literate at least among learners of transparent alphabetic writing systems. The knowledge of the early predictors of literacy development has provided means for assessing the risk of reading problems relatively early and accurately.

Naturally, the observation that children in need of support can be reliably identified years before reading instruction made JLD-researchers interested in continuing towards the most important goal – how to help preventatively and thus avoid the multiple consequences associated with difficulties in learning to read during the early grades. The preventative training based on the research findings has now been implemented in a computer game which is based on a synthetic phonics approach for helping the children master the earliest steps in reading acquisition. The game starts with the practice of grapheme-phoneme correspondences, and adapts to individual development proceeding into larger units requiring phonemic assembly skills as the child progresses. The game version supporting the early development of reading acquisition has been developed furthest, and has been localized and studied in a number of language contexts. However, the game platform and software developed allows modification of content covering further stages of reading development. The next challenges in developing training methods further relate to support of development of fluent reading after the basic phonological recoding skills are mastered, and reading comprehension as the final goal needed for acquiring full literacy.

At present, we are becoming better aware of the similarities and differences between languages and orthographies with regard to literacy development and its problems (see e.g. Seymour, Aro, & Erskine, 2003). Finnish, as a language with a very transparent orthography, is a natural contrast to the findings in the context of the lingua franca of reading research, English, that has a very opaque writing system. Thus, the findings with regard to Finnish literacy development can reveal information concerning the universalities of literacy development in alphabetic orthographies, and also raise questions concerning the possible language-related aspects of it. Concerning the applicability of the findings from Finnish to other language contexts, one should perhaps keep in mind that among the alphabetic orthographies, Finnish is less exceptional in its transparency, than English is in its opaqueness.

In this chapter we'll first summarize the basic features of Finnish language and orthography in order to give an outline of the challenges it poses for mastering the orthographic cipher, and for becoming fluent in reading. We will also summarize the most important findings of JLD with regard to early identification of problems and support of reading development, and describe the computer game -based approach for early support in reading development as well as discuss the approaches applied for supporting fluency development and reading comprehension.

2 Finnish language and Orthography[1]

Finnish is a language spoken by around six million native speakers. Finnish does not belong to Indo-European languages. Instead, it is a part of a small Fenno-Ugric (Uralic) language family together with Hungarian and Estonian, which are the other two most widely spoken Fenno-Ugric languages. Like most other languages in the group, Finnish lacks grammatical gender, has a large set of grammatical cases and an agglutinative morphology.

The Finnish phonological system is based on 24 phonemes (8 vowel sounds and 16 consonant sounds). Finnish has vowel harmony, meaning that in non-compound words there can be only either front or back vowels. Vowel harmony also applies to grammatical and derivational endings, which means that there are typically two variants of these endings. All phonemes, with the exception of a few consonants, have two phonemic quantities, short and long. In the case of stop consonants, the long quantity is produced by holding the explosion. The length distinction is lexical and grammatical, so words like *taka*, *takaa*, *takka*, *takkaa*, *taakka*, *taakkaa* have different meaning but differ only with respect to phonemic quantity. There are altogether 16 diphthongs that are considered as combinations of two distinct vowels, not as distinct phonemes. The syllable structure of Finnish is fairly simple, with ten

[1] For a more detailed description, see Aro (in press)

possible syllable structures (v, cv, vv, vc, vvc, cvc, cvv, vvc, cvvc, cvcc). Consonant clusters can be present in syllable codas, but never in word final position. Word initial consonant clusters are present only in relatively recent loan words (e.g. *strategia*). The stress pattern in spoken language is based on syllable structure, which makes syllable a perceptually salient unit in speech. The main stress is on the first syllable, and there is secondary stress on the following odd syllables.

Finnish has a rich agglutinative inflectional system. Most words (nouns, verbs, adjectives, numerals, and pronouns) in texts are inflected depending on their grammatical role in the sentence. Words can often have several affixes, so the morphological structure of a word can be fairly complex (e.g. *näytettyämmehän* translates roughly into "indeed after we have shown"). In addition to vowel harmony, morphophonological variation is present in the gradation of stop consonants, which means that inflection can cause variation between "strong" and "weak" grades of consonant, reflected as degemination of a double consonant, and lenition or assimilation of a single consonant. On top of the complex morphological system, the Finnish derivational system is rich and compounding is highly productive. For example, the word *kirja* (a book) is a source for a number of derivatives meaning a letter, the writing, a library, to write, a font, just to name a few. Correspondingly, the word *kirja* can be a part of a number of compounds. This means that compound words and derived words are frequent in texts.

The writing system of Finnish is very regular. The basic principle is a one-to-one correspondence between 23 single letter graphemes and corresponding phonemes. The sound value of each letter corresponds roughly to its value in the International Phonetic Alphabet. Of all phonemes, only the velar nasal sound does not have a distinct single letter grapheme, but is marked with letter pair *ng* when long, and with letter *n*(+*k*), when short (the short form always precedes *k*). All the other long sounds are always marked in writing by doubling the corresponding letter. Practically only departures from this one-to-one correspondence occur between morpheme boundaries, where assimilation affects pronunciation, but the spelling of morphemes is preserved. Also gemination of morpheme initial consonants can happen in some cases between morphemes in a single word, in a compound word, or at a word boundary, but this is not marked in spelling.

Because of rich inflectional system where words include a number of affixes, productive compounding and rich derivational system, Finnish words tend to be long and multimorphemic: In written texts the mean length of words is between seven and eight letters. The vast majority of words are multisyllabic: The number of monosyllabic words is around 50.

In sum, Finnish has a relatively complex morphological system, which is however phonemically transparent in writing. Morphophonological variation is also consistently marked in writing (with the aforementioned exceptions). From the point of view of a beginning reader, the bidirectionally regular grapheme-phoneme correspondences are usually relatively easy to master. With the simple G-P conversion rules, regular at the level of single letters, children can decode (and spell) any item. Phonemic assembly at the level of single letters is sufficient for word recognition, without the need to take into account any contextual effects. For a beginning reader, length of the words might pose a challenge. For this reason, in the early reading materials words are syllabified with hyphens and the reading instruction emphasizes the syllable as a sub-stage of decoding, thus relieving the memory load in decoding. One further challenge in early reading acquisition is the length contrast that seems to require a second overlapping processing cycle during decoding and especially spelling. In general, children seem to reach accurate decoding skills with ease either already before reading instruction starts, or soon thereafter. Reading disabilities are typically reflected as poor reading speed, characterized by laborious serial phonemic assembly. In its transparency, Finnish orthography might be optimal for beginning readers, and seems to help children in reaching a level of the skill allowing independent reading practice quite early. However, the challenges are related to length of the items and inflected words, requiring attention to the morphological information, typically present at the end of the long word items.

3 Supporting the Early Stages of Literacy Acquisition

The JLD started intensive follow-up from birth. Two hundred infants – half of them at familial risk due to a dyslexic parent and at least one identified close relative of the parent – and half with no identifiable reading difficulties among relatives. The earliest research observations were collected from newborns at the age of 3–5 days. Brain event-related potentials (ERPs) to syllables /ba/,/da/ and /ga/ and to sinusoidal tones consisting of repeated tones and infrequently presented pitch-deviant tones were measured in subsamples of both at risk and not-at-risk children. Both types of stimuli revealed substantial between-group processing differences which also had significant predictive correlations to the reading related measures before school age and during school. These results mean that it is possible to identify children probably in need of support in reading acquisition already during the first days of life among children who are born with a familial risk. Most of the children who have such risk factors seem to be able to overcome their problems with the help of effective early remedial instruction which is available in Finland, but a small portion of such children have problems which require starting the preventive operations at an early age. Of the roughly 50 % of children with familial risk, who face reading difficulties without preventive help, the ones (<15 % of them) with substantially delayed spoken language skills (especially receptive speech) deserve extra attention from early age. Around half of the children who face problems in early literacy development seem to have reading-related problems also after the mastery of the earliest milestones of literacy acquisition, despite well-organized remedial instruction at schools. The likelihood of continuing difficulties in acquiring sufficient reading fluency and reading comprehension is more than threefold among children with family risk as compared to those who have no such risk. Because the most typical bottleneck among readers of transparent writing is reading fluency, the most relevant help is supporting the motivation for independent reading. Most of them can be

Table 1 Developmental differences among JLD children who were at-risk and faced dyslexia (N = 33) or acquired reading skill typically (N = 68); and children of the control group who ended up reading typically (N = 77)

	At-risk with dyslexia N = 33	At-risk with NO dyslexia N = 68	Controls with NO dyslexia N = 77	F	Power
Expressive language 1.5 years	−0.26 (0.58)	0.03 (0.90)	0.05 (0.96)	1.49	0.32
Expressive language 2.5 years	0.03 (0.90)	−0.05 (0.94)	0.09 (0.78)	0.44	0.12
Morphology 5 years	−0.66 (0.89)	−0.33 (1.17)	0.01 (0.99)	4.56*	0.77
Verbal short-term memory 5 years	−0.42 (1.04)	−0.36 (1.08)	0.06 (1.01)	3.88*	0.70
Verbal short-term memory 6.5 years	−0.18 (1.26)	0.01 (1.07)	0.11 (0.98)	0.83	0.19
Phonology 5.5 years	−0.76 (0.70)	−0.31 (1.02)	0.03 (0.90)	9.89***	0.98
Phonology 6.5 years	−0.61 (0.85)	−0.26 (.97)	0.04 (0.89)	6.78**	0.92
Letter knowledge 5–5.5 years	−0.91 (0.85)	−0.26 (1.11)	0.15 (0.92)	12.28***	1.00
Letter knowledge 6.5 years	−0.89 (0.91)	−0.34 (1.20)	0.20 (0.82)	13.58***	1.00
Rapid naming 5.5 years	−1.47 (2.02)	−-0.36 (1.48)	0.08 (0.87)	13.78***	1.00
Rapid naming 6.5 year	−1.29 (1.52)	−0.37 (1.71)	0.13 (0.86)	13.13***	1.00

*p<.05, **p<.01, ***p<.001

helped successfully if their preventive support is initiated when they enter school as will be described below.

Table 1 summarizes the most relevant behavioral predictors of reading problems within the at-risk group. As observed from the table, delays of early spoken language development also predict delays in mastering written language. As Fig. 1 shows, especially problems in early receptive language development seem to be strongly linked to later reading comprehension skills at the school age, but only in the group with familial risk for dyslexia.

Delayed spoken language is not the only early predictor of difficulties a child may face in the acquisition of the basic reading skills. Table 1 reveals a number of them. Early skills seem to predict also later problems in reading development. Figure 2 depicts individual profiles in selected skills for children in the familial risk group whose reading fluency is one standard deviation lower as compared to control group children at Grade 8. Rapid naming is a generally well known predictor of reading fluency, and the data depicted in Fig. 2 shows that a large proportion of slow readers at Grade 8 had poor naming speed at the age of 6 years. However, the data shows a fairly consistent early deficit in mastering letter names. Only two of the slow readers had above average letter knowledge both at 3.5 and 6.5 years. Most of the dysfluent readers scored 1 sd below the level of the control children in letter naming at the age of 6.5 years. Letter naming is both easily administered and very helpful measure for identifying children who need more individual attention than is typically available in classroom instruction. This finding is central in our decisions

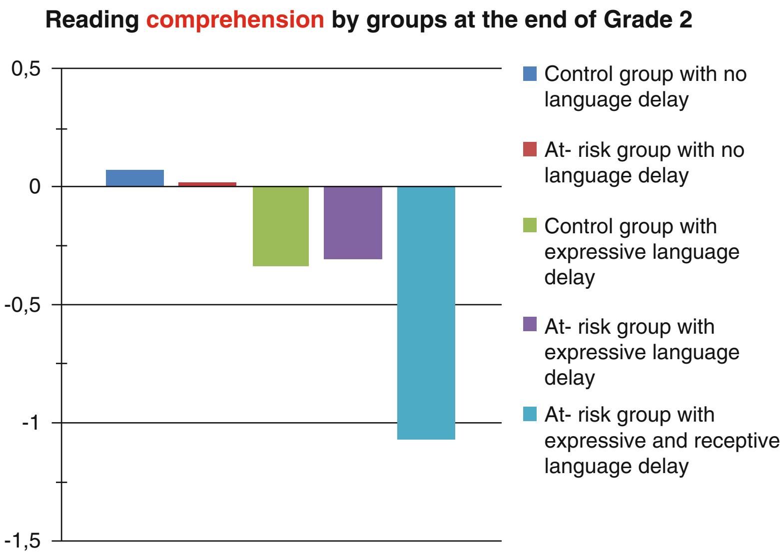

Fig. 1 Reading comprehension among JLD children according to risk-status and early language delay

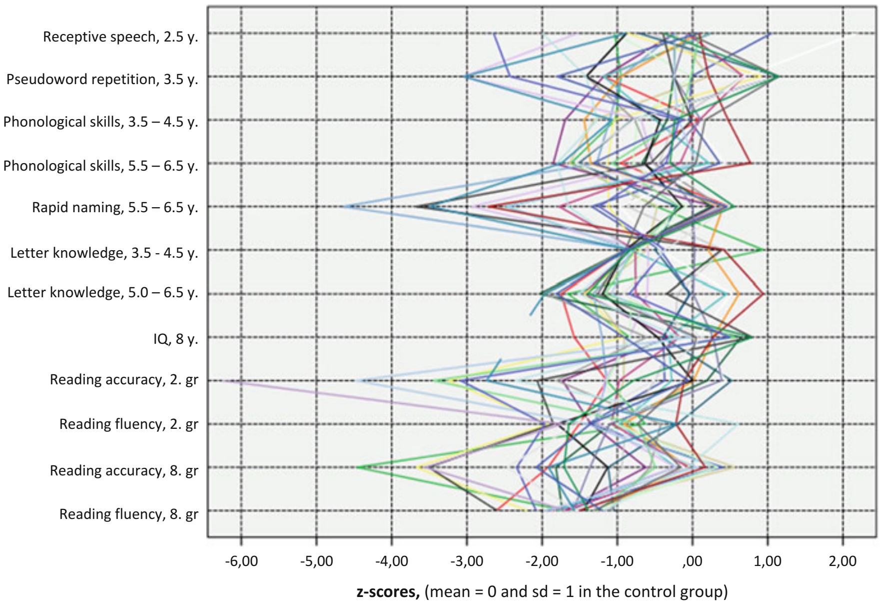

Fig. 2 Individual profiles of the most important predictor variables from age 2.5 of all JLD children with familial risk and compromised reading fluency at Grade 8

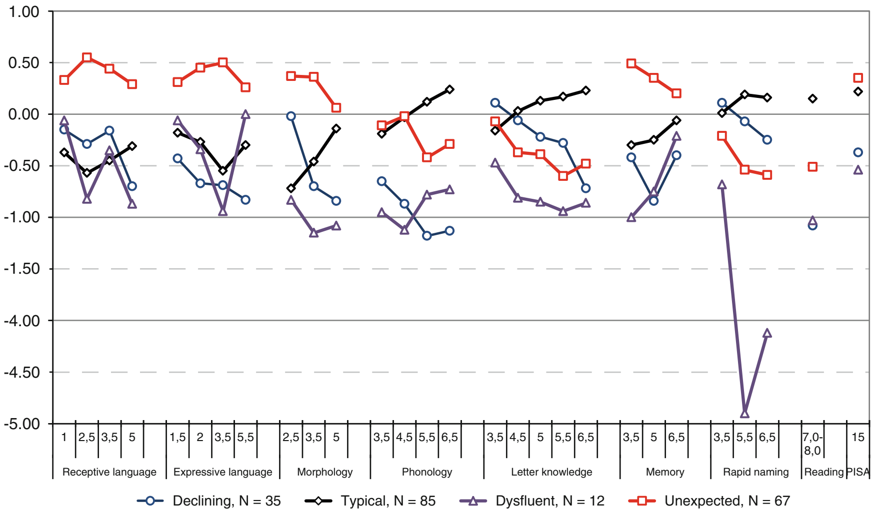

Fig. 3 Profiles of early language and memory skills for different JLD subgroups across ages 1–6.5 years, their average performance in reading and writing composite score across Grade 1 and 2, and PISA reading composite at 15 years of age (Modified from Fig. 1. in Lyytinen et al., Merrill-Palmer Quarterly, 2006)

concerning the support for early reading acquisition. Although letters are instructed at school in a way that leads to full success among a large majority of children, we ended up creating an educational game format to ensure that children are motivated in practicing their letter knowledge skills long enough to also guarantee success when the difficulties are most pronounced.

JLD-data allows a detailed look at the various developmental routes which may lead to difficulties in the acquisition of literacy. By using advanced (MPLUS) structural equation methods to differentiate sub-groups we ended up with the description of literacy development seen in Fig. 3. Altogether four main groups could be differentiated on the basis of their developmental profiles. A typical learning group consisted mostly of children from the control group without familial risk status. Another group consisted of children whose phonological development showed delays during the critical years preceding school age. This group was labelled as a group with "phonological decline", because their performance was declining relative to that of age peers. As can be seen in Fig. 3, this subgroup of children (n = 35) faced clear difficulties in learning to read. Their mean level of reading skill at the end of the second grade was more than one SD below the mean of the typically developing children. Another group with comparable difficulties in learning to decode had a very deviant pattern of naming fluency (naming dysfluency group; N = 12). Their early language development also showed delay in other skills. For this group of children, the mean level of spoken language skills during the first years of life was the lowest. They had both decoding problems and problems in achieving reading fluency, what made them the most compromised readers when age-appropriate functional reading skills were assessed at age 15, using the PISA-assessment tools. Many of the children who had intact initial development of spoken language skills faced problems in the initial acquisition of decoding skill (Unexpected group; N = 67). We called this group "unexpected" because their level of spoken language skills seemed to conflict with early reading development by the time the early reading skills were assessed (see Lyytinen et al., 2006). Later, after reaching the age when perhaps the most well-known reading assessments have been made – the PISA assessments – the performance of this group is surprising: Their reading comprehension reached highest of all the groups identified in our initial analysis, although their average profile indicated slightly delayed early reading development.

The above-mentioned learning game – called *Ekapeli* in Finland and *Graphogame* outside Finland – instructs the basic steps of reading, viz. the sounds of the letters. The further steps of support are described below in more detail, but the first step is achieved simply by motivating the child to practice letter-sound correspondences by choosing from among alternative letters falling down on a computer display, the one which represents the phoneme the player hears from the headphone at the same time. The player first learns this prerequisite skill for decoding, starting from easy to differentiate items in terms of the phonetic and visual features. The practice proceeds into covering more difficult items, and larger units (syllables and words). The program adapts to the individual learning rate, and keeps the difficulty level optimal for each learner.

All Finnish children entering school can nowadays use the game if they have any need to do so, nationwide. Every year teachers get an email message encouraging and instructing them to carry out identification of the need for extra support by assessing letter knowledge of their pupils in the first grade. This message gives guidelines for the means to motivate the child to use Graphogame as a tool for required extra support. The game further extends the identification of the individual needs via dynamic assessment during playing and adapts the game contents and parameters according to the needs revealed. After the child has played for one hour, the parents are asked for their permission to use the data for research purposes and at the same time for permission for the researchers to consult the teacher. This procedure has resulted in great popularity of the game among Finnish primary schools. During the busiest days more than 20,000 Finnish children have played the game (one age cohort in Finland is currently 60,000 children).

4 Supporting Reading Fluency in Finnish

For most children in Finland the early steps of reading acquisition are relatively easy to master. For a large percentage of children, learning the letter names at latest during the preschool year is sufficient instructional input for cracking the orthographic cipher, with the possible extra support from the parents or older siblings. Around one third of children are already accurate decoders at school entry at age 7, before any formal reading instruction (Aro, 2006; Lerkkanen, Rasku-Puttonen, Aunola, & Nurmi, 2004). A number of children are able to read books at that point, and are even relatively experienced and fluent readers. The Finnish letter names systematically include the corresponding letter sounds, and typically children master letter names relatively well at school entry. Reading instruction based on synthetic phonics can be thought of as a strong intervention for the phonological skills in a transparent orthography, since letters act as reliable visual markers of spoken language phonemes. Spelling instruction that starts simultaneously with reading instruction further supports phonological analysis skills.

Although this first threshold into becoming a reader might be lowered by the features of orthography, there are other challenges for the beginning reader. The words are relatively long, due to derivational and grammatical inflections, as well as compounding. Thus, serial phonological assembly on the level of single letters is a slow route for getting to word level information. It is also demanding for phonological and working memory, even when using syllables as a sub-stage of recoding. The need for accurate decoding is further underlined by the rich morphological content of words, especially in a number of suffixes, which means that a lot of morphological information is coded in the endings. Therefore, recognition of the lemma does not suffice for understanding the meaning in the specific context. For this reason, whole word recognition does not serve as an initial reading strategy. As an example, any Finnish noun can have over 2,000 different word forms depending on the inflections. For understanding the text, the morphological information after the root also needs to be accurately decoded and processed. Therefore, the early instruction during the first school year emphasizes accurate decoding. Fluent reading is usually not instructed explicitly. It is supported mostly by programmes aiming at encouraging and motivating children for independent reading and increased reading experience.

For many children the serial phonemic assembly remains as the processing strategy after the initial stages of reading instruction and the speed of reading remains slow. Typically, the reading problems after the very early stages of reading acquisition are characterized by slow reading, often despite good accuracy. Usually the children struggling with reading speed do not read much outside the school setting, so the gap with age peers does not seem to narrow. While it seems clear that especially poor reading speed is a universal characteristic of dyslexia (Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003), it is also evident that the development towards fluent and automatic reading skill is much more poorly understood than the early development towards accurate word recognition, as summarized eloquently by Share (2008). As is the case with accuracy development, orthography can be supposed to also play a role in fluency development. The typical English models of reading acquisition describing two separate processing routes (indirect assembly/direct recognition) do not seem fully applicable to a language with a complex inflectional morphology. The basic questions are first, what are the units of processing in automatic and effortless fluent reading, and second, how can the development of fluency be supported in children who seem unable to make the suggested developmental shift from the slow serial assembly of pronunciations.

Theoretically, there are many options for the linguistic unit relevant in reading fluency development, when considering Finnish. It might be possible that the phonological processes at the level of single grapheme-phoneme pairs become fully automatized. Another option is that with increased experience of written language, recognition of larger units like letter combinations (restricted by phonotactic constraints) surpasses processing at the level of single letters. Further, since syllable is a salient unit of spoken language, and also explicitly emphasized and used in early reading instruction, it is possible that reading fluency development is guided by recognition of syllables as larger units. Since Finnish words are multimorphemic, also morphemes like inflectional endings and other suffixes might with experience become larger units utilized in fluent reading. Lastly, it is possible that fluent reading is guided by direct word recognition. A number of words, like most function words, are not inflected in Finnish, and they are also very frequent in the texts, making them a plausible candidate for direct recognition. Of course these options do not exclude each other. It is possible that all or many of these linguistic units are important in fluent reading, or that there are developmental shifts in the emphasis and importance of these units during the course of fluency development.

The fluency training found in the literature can be broadly divided into two approaches (see Huemer, 2009). The first one stems from the educational tradition, and has aimed at increasing the amount of (supervised) reading practice. Varying methods have been used, including paired reading, peer tutoring, or group-based practices. The results have been generally positive, but the effect sizes rather small. The second approach covers varying approaches of repeated reading, which typically means drilled practice: Repetitive reading of predetermined lists of words, sentences or texts. The basic idea is to increase and strengthen word-specific knowledge that would facilitate reading outside of practice context. To summarize the findings, the repetitions affect the recognition speed of the practiced items, but the effects are item-specific, meaning that they do not transfer over and above the practiced material (see Berends & Reitsma, 2006).

Our initial starting point in fluency training was to investigate whether structured repetition-based practice aiming at utilizing larger units would create improvement in the speed of processing written language. Of the above mentioned options as possible larger units, words are not the first choice in Finnish due to the huge number of possible inflected forms most words can have. If the effects of repeated reading practice are item-specific, the effects of the word-level practice would be practically minimal. Since letter combinations and morphemes are not easily pronounceable without word context as units in a drill-based reading practice, they were not the choice either. Instead, we have targeted the syllable as a possible unit of automatic recognition. Firstly, syllable is a familiar unit of language for the children both phonologically and orthographically. Secondly, even when the effects would be item-specific, they could be hypothesized to generalize into reading outside the specific practice items. The number of syllables is rather limited in Finnish, the number of distinct syllables being around 2500 (Karlsson, 1983).

The main findings of our studies with regard to repeated syllable practice have been published by Huemer, Aro, Landerl, and Lyytinen (2010) and Heikkilä, Aro, Närhi, Westerholm, and Ahonen (2013). Huemer et al. (2010) reported a quasi-experimental study with a switching replications design, where the effects of syllable practice were assessed in a group of slow readers at grade levels 3–6. The children practiced reading aloud a predefined set of very infrequent syllables on a computer, and the effects of practice were assessed with a number of list reading tasks covering practiced items, pseudowords including practiced syllables, and a text including no practiced syllables to control for the specificity of the effects. Altogether children received 50 repetitions of the set of 30 practice syllables during daily 10 min sessions for 2 weeks. After training, the speed of reading the list of practiced syllables was significantly faster, but more importantly, also the speed of reading bisyllabic pseudowords including practiced syllables. No treatment effect was observed on control text reading speed, which supports the idea of item-specificity of the effects of repeated reading, but also indicated that the effect was not due to more general, e.g. motivational, factors.

The study described above was not an intervention study as such, but rather a test of the applicability of syllable-based training, although it was carried out within an intervention design. We used very infrequent syllables to ensure that the children had not encountered them before. That, of course, means that there is also no real transfer effect into everyday reading. Further, the means of repeated reading practice were not designed as an intervention tool, but served more experimental needs. To take a step into applying the repeated reading of syllables as a practice in a more real training context, Heikkilä et al. (2013) adapted the concept of repeated reading with syllables in the Graphogame (GG) platform. Since GG is developed as a motivational game setting, which gives consistent feedback and adapts to the performance level of the child, it is a much more suitable context for real-life interventions. The findings of the study with 150 poor readers replicated the basic findings of Huemer et al. (2010), with reference to specificity of the training effects: It was restricted to practiced items. In this study, the findings of Huemer et al. concerning the transfer into pseudowords containing the practiced syllables were also replicated, although the effect sizes were smaller than in Huemer et al., and the findings were restricted to long and infrequent syllables. The observed differences in effect sizes and transfer might be attributable to several differences between the studies. First, GG training did not require reading aloud, which might be less efficient from the point of view of repeated reading. This effect might be further amplified by assessment methods being based on reading aloud. Further, the training effects might be sensitive to the type of syllables to be practiced. In the Heikkilä et al. study, the transfer was observed only with longer and infrequent syllables, where also strongest training effects on the level of reading the practiced items were observed. This could mean that repeated reading training with sublexical units, like syllables, requires careful selection of the syllables to be practiced: It might be most useful to select practice items not yet fully automatized, but frequent enough to expect transfer into everyday reading. In sum, the studies mentioned above show that – at least at a certain point of reading development – practice based on syllable reading might be useful for slow readers in increasing fluency and supporting more holistic reading processes.

It seems plausible that the development of fluent reading is not only guided by changes in reading related cognitive processing. Share (1995) has postulated self-teaching as a basic mechanism for fluency development. The self-teaching hypothesis basically states that after the decoding skills have developed to a level allowing independent reading practice, fluency development is mostly determined by the experience children gain from independent reading. Repeatedly encountering orthographic representations of words allows refined learning of regularities and constraints governing written language, and also gradually increases word-specific information required for rapid access to pronunciation and meaning. However, independent reading outside the school setting is often most limited in children in need of it the most. The level of skill is usually related to motivation for practicing or using it. Anderson, Wilson and Fielding (1988) reported that in the decile of children reading most outside the school setting, the time spent for reading in 2 days equals the amount of reading during a year in the decile of children who read the least. So, the differences in independent reading practice seem huge.

To support reading practice, Finnish schools typically apply a "reading diploma" programme for children at grade levels 1–6. It is basically a year long (voluntary) project where participating children can select and read books from a list covering various types of literature. According to the predefined criteria for the number of books to be read, the children receive a diploma (or various levels of diploma) at the end of school year. The programme is supposed to familiarize children with literature and also increase the reading experience, as well as to motivate reading. Another cultural aspect that is known to be supportive of reading motivation in Finland is the use of subtitles instead of dubbing for foreign-language programs in television or cinemas. For children, the ability to follow subtitles is a natural criterion of functional reading ability, and reaching that skill level is often motivating the kids for practicing their reading fluency further.

Further, issues such as motivation and self-beliefs also deserve attention in intervention research. In our ongoing projects we have assessed task-related self-efficacy, motivation and skill development in a longitudinal setting and hope to reveal information about the interplay between self-beliefs, motivation and skill development. In the project we also investigate whether self-efficacy can be supported in a peer group programme led by special education teachers, and whether this support boosts the effects of skill-related practice. Our hypothesis is that performance-related positive feedback and peer support could help in overcoming problems related to poor motivation or poor belief in one's ability to develop one's skills that is often characteristic for learning disabled children. In another ongoing developmental project the effect of peer reading sessions offered by elderly volunteers at schools is being assessed. Since the projects are ongoing, not much can be said yet about the results. However, since knowledge about evidence-based means for supporting reading fluency is relatively limited, we should perhaps broaden our scope also outside purely cognitive and skill-related domains.

5 Supporting Reading Comprehension

The final goal of reading, full literacy, means the ability to use the written world optimally, to be able to follow the meaning mediated via text. Comprehension of written sentences is a challenging task for early readers who have to divide their cognitive resources between decoding and comprehension. Comprehension requires mediating the meanings of the words and syntax in mind at a speed which does not overload the limited working memory capacity. This means that a substantially high reading fluency has to be reached before long sentences are read at a sufficient speed. The natural and necessary way to achieve such automaticity of reading requires a lot of reading – the most important practice a child needs for becoming fully literate. In the rich western world most children have access to materials made for early readers, exciting enough for motivating the child to read. But access to reading does not guarantee reading practice. In environments where economical conditions of families are poorer, publishers decide not to print books for children due to low demand. Children in underdeveloped environments, as well as many children in developed countries would benefit from opportunities to have an enjoyable and motivating environment supporting these final steps towards full literacy. This is why we are preparing a reading comprehension training tool using Graphogame in collaboration with the experts developing the MindStar books (Ward et al., 2013). Their readiness for using computer technology for machine-based translation of languages makes it possible to have the materials we are developing for English and Finnish in our collaborative project also available for readers of other languages.

The main logic we follow in this final training stage is helping children to understand why we are reading, and helping them learn the optimal attitude and strategy for approaching texts. Exciting science-technology-engineering-mathematics (STEM) contents are chosen to be used for this purpose because these are helpful in whatever cultural context the child happens to live. The plan is to have available the hundred most important contents children have to learn as soon they reach an appropriate reading skill. To elevate understanding of the content mediated via text, we use multiple ways to increase the likelihood that learners become able to comprehend the main points. Animations and other visual means are used to complement the written materials. Most importantly, we will provide a virtual teacher and/or author of the text, from whom the readers can ask help if needed. This help can be made to not only explain the meanings of hard-to-understand items in the text, but also to indicate how such meaning can be reached by using the written material in an optimal manner. Early readers need support in identifying the optimal strategy for approaching written material, because it is dependent on the nature of the content in a complex way. The very same approach could be implemented within other digital contexts where written information is available today. Although children become digitally native earlier and earlier, the strategies for learning in new media are rarely instructed. Digital techniques could offer instructional tools also in making these new learning contexts more approachable for everyone. Unfortunately, this is rarely the case, as seen for example in the solutions where tablet-based school instruction materials are offered in the form of pdf-copies of the traditional books. There is a lot of room for development, since the very same learning goals could be reached much more efficiently if the digitally mediated content would be offered in a form using all the versatile possibilities of such dynamically programmable devices – Graphogame being one example what this could mean.

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Training Reading Fluency and Comprehension of Spanish Children with Dyslexia

Carmen López-Escribano

Abstract First, we present a summary of reading and dyslexia research in the Spanish language. Although reading research in Spanish has followed English research, studies are less numerous in Spanish and have appeared later in time. During the 1990s, Spanish studies on reading focused on phonological processing. Recent studies have examined other aspects of reading and have shown that impaired *reading rate* is a distinctive feature of individuals with dyslexia in Spanish. In Spanish, as in other transparent orthographies, reading speed problems seem to be more evident and relevant than accuracy problems.

Secondly, we examine whether the computerized Reading Accelerated Program (RAP) enhances the sentence reading rate and the reading comprehension of 12 Spanish children with dyslexia, and whether the results found in this program transfer to reading printed material. Training results showed that children with dyslexia were able to increase their sentence reading rate and comprehension level when pushed to do so with accelerated reading training, providing evidence for the Acceleration Phenomenon. Post-test results, showed significant gains in rapid naming of letters, pseudoword reading time, and visual symbol search. Finally, we discuss results with regard to future lines of research on reading fluency to improve the effectiveness of interventions directed at Spanish children with developmental dyslexia.

Keywords Reading intervention • Training • Reading disability • Reading acceleration • Dyslexia • Comprehension • Reading fluency

1 Introduction

According to a widely held hypothesis, dyslexia is primarily a language disorder characterized by difficulty in distinguishing between speech sounds (Mody, Studdert-Kennedy, & Brady, 1997). Individuals with dyslexia are also characterized

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by inaccurate and slow reading and often exhibit naming speed deficits (Jones, Ashby, & Branigan, 2013; Wolf & Bowers, 1999). It is known that dyslexic readers show impaired ability to coordinate the many components necessary for fluent reading (Jones et al., 2013; Wijnants, Hasselman, Cox, Bosman, & Van Orden, 2012).

Research on dyslexia in Spanish has followed the same trends as in English, but Spanish studies are not as numerous as English, and have been published later in time. For many years, research on dyslexia in Spanish, as well as in English, has mainly focused on phonological processing and accurate reading, and showed that students with dyslexia experienced difficulties in phonological processing (Jiménez, 2012).

However, inter-cultural studies suggest that the level of orthographic transparency determines the reading performance of dyslexic children (Seymour, Aro, & Erskine, 2003; Ziegler & Goswami, 2005). In opaque orthographies, the fundamental feature of developmental dyslexia is difficulty in reading accuracy, whereas slower reading speed is more common in transparent orthographies. In languages where a regular structure can be decoded using relatively low levels of phonological skill, the problems of children with reading disabilities are characterized by problems in fluent word decoding rather than pure phonological deficits (Landerl & Wimmer, 2008; Re, Tressoldi, Cornoldi, & Lucangeli, 2011).

Spanish studies on reading disabilities indicated that phonological skills, as assessed by the testing of phonemic awareness or nonsense word decoding, are related to reading and spelling acquisition. However, findings have also indicated that pure phonological deficits are less manifested in the Spanish language since Spanish grapheme-phoneme correspondence is regular. Recent research has provided evidence that the problems of children with dyslexia may not be restricted to the phonological domain. In fact, poor readers in Spanish often read words with accuracy and their main reading problem is decoding unusual or complex words and nonwords that are read fluently by average readers (Jiménez 1997; Jiménez & Hernández-Valle, 2000; Jiménez & Ramírez, 2002; Rodrigo & Jiménez, 1999). Also, in a transparent language such as Spanish, children may develop their reading ability normally during the first school year, with suitable reading instruction.

Following the same trends as in English, later studies on dyslexia in Spanish have focused on difficulties in fluent reading (Davies, Cuetos, & González-Seijas, 2007; Davies, Rodríguez-Ferreiro, Suárez, & Cuetos, 2013; Escribano, 2007; Kim & Pallante, 2012; Serrano & Defior, 2008; Suárez & Cuetos, 2012a). Currently, a number of additional skills related to fluency such as reading rate, rapid naming (RAN), and prosody, have been also studied in the Spanish language.

Studies on prosody and reading performance in Spanish have reported that the *knowledge of stress rules or stress sensitivity*: (1) is related to fluent reading and reading comprehension (Calet, Defior, & Gutiérrez-Palma, 2013); (2) predicts reading acquisition (Goswami et al., 2010); and (3) predicts differences in reading between adults readers coming from different cultural backgrounds (Suro et al., 2009).

López-Escribano, Suro, Leal, and Sánchez's research, (2014) reviewed 32 studies on rapid-naming (RAN) in Spanish. The main conclusions of this review are: (1) RAN Colours, Objects and Letters performance in preschool predicts word reading and reading speed during the first years of primary school; (2) RAN is the best predictor of reading speed or fluency in the Spanish language; (3) phonological awareness and RAN are independent predictors of reading; (4) there are significant differences in RAN between average readers and readers with difficulties; and (5) children with double deficit show more difficulties in reading than children with a single deficit (phonological deficit or speed deficit).

Besides reading speed, spelling is another source of difficulty for dyslexic readers of Spanish (Escribano, 2007; Goswami, 2010; Jiménez, Rodríguez, & Ramírez, 2009; Serrano & Defior, 2012b). Spelling problems are due to the fact that Spanish has a consistent orthography for reading, but to a lesser extent in writing. That is to say, certain words contain phonemes that are represented by a variety of graphemes, with no phonological rule specifying the appropriate grapheme for the correct word spelling. For instance, the [b] sound is represented by the letters "b" and "v". According to the different explanatory theories of dyslexia, successful interventions need to be focused on the different dimensions that underpin the manifested disorders (Norton & Wolf, 2012; Snowling & Hulme, 2012; Wolf & Katzir-Cohen, 2001). Consequently, it is important to understand which features of intervention are beneficial for *slow dyslexic* readers *and poor spellers*.

2 Reading Instruction in Spanish

In Spanish, reading instruction proceeds usually from smaller to larger units. Syllables are the most consistent sub-lexical units in Spanish both for reading and for spelling (Carreiras, Alvarez, & de Vega, 1993; Carreiras & Grainger, 2004). In Spanish, the syllable has clearly defined boundaries and children easily learn to distinguish syllables, in particular the prototypical syllable of consonant followed by a vowel (CV). There are 19 types of syllables structures in the Spanish language, the most frequent types are: CV as in "casa" [house]; CVC as in "palmas" [applause; clapping]; V as in "oso" [bear]; VC as in "andar" [walk]; CVV as in "agua" [water]; CCV as in "plato" [plate]; CVVC as in "guante" [glove]. The rest of syllable structures are less frequent (Guerra, 1983).

Although the letter and syllable-assembly teaching method provides for the possibility of reading accurately from the beginning of reading acquisition, it is also important to understand how to enhance reading fluency, spelling, and reading comprehension in dyslexic readers. Nevertheless, because the theory of the phonological deficit has been widely investigated in recent years in the Spanish language as an explanation of reading disability, the development of training programs has focused primarily on the phonological component of reading (Cuetos et al., 2003; Defior, 1996, 2008; Jiménez & Ortiz, 2000; Suárez, 2009). Interventions in one specific area, such as phonological awareness, are tailored to improve phonological awareness itself and decoding, and do not always have an impact on other related reading abilities, such as, reading comprehension (Defior, 2008; Snowling & Hulme, 2012).

In contrast to studies that target either the prevention or remediation of students identified with decoding difficulties, there are few examples of interventions targeting reading fluency. Currently, researchers are investigating the effects of multicomponent programs to improve reading fluency and text comprehension in Spanish children with dyslexia. The multi-componential reading program by Soriano, Miranda, Soriano, Nievas and Félix, (2011) includes different strategies, such as training in phonological awareness, grapheme-phoneme decoding, and repeated reading. The study by Soriano et al. (2011) claimed to have benefits in word reading and text reading fluency but no significant improvements in reading comprehension.

However, research does not always have a quick impact on practice and currently a range of different approaches to treat reading difficulties coexist in schools: from reading aloud and phonological awareness training, to visual-spatial orientation methods of intervention. Contrary to results of a line of studies (e.g., Suárez & Cuetos, 2012b; Von Károlyi, Winner, Gray, & Sherman, 2003), there still exists among some professionals as well as the public, the belief that difficulties in visual or spatial-orientation ability is the cause of dyslexia.

3 Reading Fluency

Probably, due to the characteristics of the language, a large number of dyslexic Spanish children are able to overcome some of their decoding accuracy limitation, yet continue to be slow readers and poor spellers. This fact shows that fluent reading is not always an outcome of the effectiveness of decoding accuracy. The relation between accuracy and fluency in reading are not yet fully understood. Although related, it seems that accuracy and fluency are two different processes (Breznitz, 2006).

According to recent studies, reading fluency could be defined as "reading accurately at a quick rate with appropriate prosody and allocating attention to comprehension" (Hudson, Pullen, Lane, & Torgesen, 2009; Wolf & Katzir-Cohen, 2001). Two influential theories of reading development, LaBerge and Samuels's (1974) *automaticity theory*, and Perfetti's (1985) *verbal efficiency theory*, may have contributed to substantial research being conducted on the influence of reading fluency on reading comprehension. Text comprehension models in reading research posit that slow word recognition inhibits reading speed and decreases comprehension. According to these theories, automatic, effortless rates of processing releases cognitive resources such as working memory and attention making them available for the higher cognitive processes involved in comprehension. If attention is consumed by decoding, no capacity is available for the attention-demanding process of comprehension.

Fluency in reading is difficult to improve by intervention (Hintikka, Landerl, Aro, & Lyytinen, 2008; Thaler, Ebner, Wimmer, & Landerl, 2004). The most commonly used method for facilitating fluency is the repeated reading technique (Samuels, 1979). Here readers are simply asked to read a list of words or a passage of connected text, at a level appropriate to the learner several times, until a particular reading rate -words per minute- is attained. However, recent review studies by Chard, Ketterlin-Geller, Scott, Doabler, and Apichatabutra (2009), and O'Keeffe et al. (2012) suggest that repeated reading does "*not qualify as an evident-based or promising practice for students with learning disabilities*". Standard remediation protocols, as repeated reading or reading aloud, seem to have little effect on dyslexic readers, probably because the visual route is not activated by these techniques, and poor reading skills persist into adulthood in many cases. Besides, the repeated reading technique is restricted to oral reading, which requires guidance of a teacher to provide correction to each individual participant and thus is an expensive procedure.

Accordingly, the *Reading Acceleration Program* (RAP) (Breznitz, & Bloch, 2012) provides a different approach to treat slow reading. This approach has been used to enhance reading rate in silent reading. As reading rate is a basic component of reading fluency, it was hypothesized that fluency can benefit from training by imposing time constrains. Breznitz, has shown in a series of experiments, that reading speed can be treated not only as an outcome of the effectiveness of word recognition skills and comprehension (dependent) variable, but also as an independent variable that influences the quality of reading skills and can be manipulated experimentally. In this regard, the *Acceleration Phenomenon* (AP) implies that fluency and comprehension improve for readers when forced to read faster (Breznitz, 2006).

However, many teachers believe that decoding accuracy is crucial for reading comprehension and conceptualize reading fluency exclusively on reading speed. They see fast reading as a negative aspect of reading: "*Children need to slow down their reading and pay attention to what they read to avoid mistakes and comprehend the text*" is a common saying among teachers. The problem, as Breznitz (2006) states it, is that as a result of numerous years of poor reading habits (possibly related to the tendency of teachers to slow down students' reading rates) the process of retrieving words via direct retrieval cannot be self-activated.

A growing number of studies on the AP (Breznitz, 1987, 1988, 1997a, 1997b, 2006; Breznitz & Leikin, 2000; Breznitz et al., 2013; Chuntonov & Breznitz, 2012; Horowitz-Kraus & Breznitz, 2014; Karni et al., 2005; Niedo, Yen-Ling, Breznitz, & Berninger 2014; Snellings, van der Leij, de Jong, & Blok, 2009), using experimental manipulations, electrophysiological and/or behavioural measures, have shown that reading improves if readers are induced to read faster and that the brain may be able to process information at a faster rate that is normally attempted. This seems particularly true for novice and dyslexic readers because this population has more to gain in terms of reading rate. In fact, these studies show that reading acceleration influences various cognitive processes that are activated in effective reading. Acceleration extends attention span, reduces distractibility, helps overcome some of the capacity limitations of short-term memory and enhances working memory processing. In addition, it increases word retrieval from the mental lexicon. During the acceleration of reading rate, all readers increased decoding effectiveness by reducing decoding errors. In addition, under the fast-paced condition, readers also increased their comprehension scores significantly. It has been also suggested that accelerated training reduced the overall reliance on the impaired phonological route of readers with disabilities (Breznitz, 2006). As a consequence, acceleration training may be a promising approach because its effects seemed not to be restricted to the specific target words in the training.

The effects of accelerated training were also investigated in the Spanish language through the program of *Reading Fluency Intervention* [Intervención en la fluidez lectora], (Serrano & Defior, 2012a). This program combines repeated and accelerated reading and phonological awareness activities. It works at the syllable, word, and text reading levels. The aim of the program is to automatize the reading of sublexical units, which are easily recognizable in Spanish, in order to facilitate faster and more efficient word recognition. A preliminary intervention case study (Serrano & Defior, 2012a) showed post-test positive training effects in transfer to routine reading, reduced decoding errors and increased reading speed. The actual AP, however, was not tested in this study. As far as we know, the AP has not yet been studied in the Spanish language.

The main purpose of this study was to extend the research on the effects of the AP to Spanish. More specifically, our main objective was to examine whether children with dyslexia benefit from a training in which reading rate was experimentally manipulated. We investigated both development during computerized training and transfer effects to routine reading. The following questions were considered:

Is the AP applicable to children with dyslexia in Spanish? i.e.: is it possible for dyslexic children to increase their comprehension levels when forced to read faster using the RAP? Do RAN, accuracy, reading rate, and reading comprehension in routine reading increase in children with dyslexia after training with the RAP? Would the accelerated reading training have an effect on visual attention (tested in a visual symbol search task)?

4 Method

Participants

Twelve primary school students with dyslexia participated in the study. Six fourth graders and six fifth graders, ranging from 10 to 12 years of age (mean age 10 years, 7 months; SD = 4 months). Eight were males and four females and all were native Spanish speakers from a middle class background. The participants were sampled from one school that specialized in the treatment of learning disabilities. The 12 participants in this study had been diagnosed with dyslexia by a specialist. Ten of them presented significant spelling difficulties; five significant slow reading; and two of them accuracy problems. All of them had average or above average scores in reading comprehension.

The presence of reading difficulties was further confirmed using the standardized PROLEC-R test of Spanish pseudoword reading and reading comprehension (Cuetos, Rodríguez, Ruano, & Arribas, 2007), and the orthographic choice task of the Reading Assessment Battery [Batería de Evaluación de la Lectura] (López-

Higues, Mayoral, & Villoria, 2002). The requirements following the assessment were a score corresponding to the 25th percentile or less. There was no evidence or history of neurological damage, environmental disadvantage, emotional disturbance, hearing or vision impairments, or any other major handicapping condition, in accordance with the conventional exclusion criteria for learning disabilities.

Design

All children were assigned to the same *accelerated training* condition. Before and after training, all students performed three tests in groups (orthographic choice task, reading comprehension of connected text, and a symbol search task), and three individually (RAN-letters, pseudoword reading and connected text reading).

Training Regime

The Spanish version of the Reading Accelerated Program used in this study was translated and culturally adapted from an English version, meant for children from Grade 2 to Grade 6. This English version was provided by the Edmond J. Safra Brain Research Centre for the Study of Learning Disabilities at the University of Haifa.

The Spanish version had 600 sentences with their three possible multiple choice answers to corresponding questions. Each individual, depending on his/her reading rate, had around 10 h of training, carried out in five 30 min weekly sessions administered over a 4-week period (a total of 20 sessions). Each session consisted of 30 sentences with corresponding questions. The first (Session 1), and the last session (Session 20) consisted of pre- and post-tests, both with 15 sentences at *self-paced* (unaccelerated reading condition) and 15 sentences at *fast-paced* (accelerated reading condition). The per-letter disappearance rate was the fastest average per-letter rate calculated from the self-paced condition for sentences that were correctly comprehended. Children worked independently and silently on a computer, under the supervision of a trained graduate student, after receiving instructions. The sentences appeared one at a time on a computer screen, and participants were instructed to begin reading each item immediately upon its appearance on screen. After reading a sentence, the participant pressed the spacebar, the text consequently disappeared, and was followed by a comprehension question that appeared on the computer screen with three multiple-choice answers. The participant was requested to choose the correct answer by pressing the corresponding key on the keyboard. All children were presented with the same set of sentences in the same order during training. Reading time and comprehension were recorded for each sentence throughout training.

The Reading Acceleration Training Paradigm

In the first training session (pre-test) initial speed was established by means of 15 self-paced sentences. This session generated a letter reading rate for each question correctly comprehended. Next, a block of another 15 sentences and their questions was presented with the letters in each item made to disappear one by one. "Disappearing" started at the beginning of the sentence, based on the child's best per letter reading time as calculated in the established parameters. Each training unit had 30 sentences. In each unit, whenever a child had more than 20 % incorrect answers in a row of ten sentences, the program decreased the reading rate. The per-letter "disappearance rate" decreased in steps of 1.5 ms. When the child's answers were 100 % correct in a row of ten sentences, reading rate would gradually increase, the per-letter "disappearance rate" increased in steps of 1.5 ms. When the child's correct answers in a row of ten sentences, were between 80 and 100 %, the "disappearance rate" remained constant. A stair-case procedure was used. At each session, a child would start at the rate that was reached at the end of the previous session.

Pre- and Post-Test

The pre-test was the first session of the program; the post-test was the last session of the program. Both, pre- and post-test included a self-paced (15 sentences) and a fast-paced (15 sentences) condition.

Self-Paced Condition In the self-paced condition, two different forms (pre- and post-test) were administered to obtain a measure of the participant's usual self-paced reading rate. This test started with two practice sentences, followed by 15 test sentences. Each sentence appeared and remained in its entirety on the computer screen. The multiple-choice comprehension question with three possible answers was presented immediately after the child pressed the spacebar, which terminated the presentation of the sentence. Reading time and comprehension of each sentence were recorded for each child.

Fast-Paced Condition In the fast-paced condition, there were also two different forms (pre- and post-test). The test had 15 sentences and their corresponding questions. Each sentence appeared in its entirety on the computer screen and was immediately erased starting from the left, in a letter-by-letter manner. Disappearance rate was the fastest average per-letter rate calculated from the self-paced test for sentences that were correctly comprehended. A multiple choice comprehension-testing question was given for each item after the child pressed the spacebar to signal termination of reading.

The paper and pencil tests administered individually were:

RAN-Letters. Rapid Automatized Naming of Letters (RAN-L) This task was selected from the RAN/RAS test (Wolf & Denckla, 2005). The task requires the student to name as quickly as possible five letters that are repeated ten times. These letters are distributed across a page consisting of five rows and ten columns. It has 50 letters in total. The test-retest reliability standard reported for this test is 0.90 (the same form was administered in the pre- and post-tests).

Pseudoword Reading Accuracy and Time. PROLEC-R, Evaluation of Reading Processes for Children – Revised Edition (Cuetos et al., 2007) To assess the accuracy and the reading time of pseudo-words, we used a pseudoword reading test that consists of 24 pseudo-words. We took the total pseudo-word reading time (PWRT) along with the number of errors committed when reading in order to measure pseudo-word reading efficiency (PWRP). The index of reliability measured with Crombach's alpha for this standardized test is reported to be 0.79 (the same form was administered in the pre- and post-tests).

Per-Word Oral Reading Time and Decoding Errors in Connected Text This task consisted of reading, for 90 s, part of a story. The two texts (pre- and post-test) used in the experiment, *Puffins Night* [La Noche de los Frailecillos], 822 words, and *The Upside-down Mice* [Los Ratones Patas Arriba], 526 words, were taken from the Progress in International Reading Literacy Study (PIRLS, 2001–2006) –the program promoted by the International Association for the Evaluation of Educational Achievement (IEA). The two selected texts were meant for fourth grade students. We took the total number of words read in 90 s, along with the number of errors committed when reading in order to measure word reading efficiency.

The paper and pencil tests administered in groups were:

Orthographic Choice Task (OCT) This task consists of a text adapted from the *Orthographic Rules* subtext taken from the Reading Assessment Battery [Batería de Evaluación de la Lectura] of López-Higes et al. (2002). In this task, participants must choose the word that is spelled correctly after being given one word alongside two pseudowords, both pseudo-homophones phonologically identical. For instance, the target word "zanahoria" [carrot] is phonologically identical with the two pseudowords "zanaoriah" and "zanaoria." The reliability of this test, using a split-half method of reliability, is 0.77 for the first ten word triplets and 0.60 for the last ten triplets (the same form was administered in the pre- and post-tests).

Reading Comprehension of Connected Text (PROLEC-R, Evaluation of Reading Processes for Children – Revised Edition) (Cuetos et al., 2007) To assess reading comprehension, we used the PROLEC-R Reading Comprehension Test (PROLEC-C). PROLEC-C consists of four short narrative texts that participants have to read silently followed by 16 open inferential questions. We used parallel forms in the pre and post-tests: texts 1 and 3 from the battery for the pre-test, and texts 2 and 4 for the post-test. Cronbach's alpha reliability index reported for the norm of this test is 0.79.

WISC-IV Symbol Search Subtest (Weschler, 2005) Children were given rows of symbols and target symbols, and asked to mark whether or not the target symbols appear in each row (the same form was administered in the pre- and post-tests)

5 Results

Training Results on Reading Rate and Comprehension

In order to examine how the acceleration training influenced the reading process, we examined both reading rate and comprehension during the training.

The parameters of the acceleration training program indicated some gains in reading rate for 4 of the participants (their per-letter reading time decrease), their reading rate mean during the 18 training sessions, was 139.32 ms per letter, their reading comprehension was stable for them, with a reading comprehension mean score of 89 % of correct answers (see Figs. 1 and 2). In contrast, for the other eight readers, the parameters indicated a constant increase in their reading rate, (their per-letter reading time increase), their mean reading rate during training was 195.36 ms per letter, reading comprehension was stable for them too during training, reaching a mean comprehension score, of 68 % of correct answers in the training sessions (see Figs. 1 and 2). T-test for independent samples indicated a significant difference in reading rate ($t=-5$; $p=0.000$), as well as, in reading comprehension ($t=10.36$; $p=0.000$) between these two groups. Based on these differences, participants were assigned into two reading groups: *proficient comprehenders* and *less proficient comprenhenders*.

The slight decrease of the per-letter reading time, for the proficient comprehenders, and the increase in the per-letter reading time, for the less proficient comprehenders (see Fig. 1) could be explained by the specific paradigm of reading acceleration used in the present study. In the previous studies examining the RAP, consistent decrease in reading time was found throughout training (e.g., Breznitz et al., 2013; Snellings et al., 2009). These studies, however, used a different threshold for applying the staircase procedure of letter disappearance than the one used in this study: while the previous studies demanded 60–80 % correctly answered questions before the per-letter reading time decreased, in our experiment children had to answer 100 % of correct answers to decrease the per-letter reading time. It may not have been easy, and particularly for the poor comprehenders, to maintain this level of comprehension throughout training.

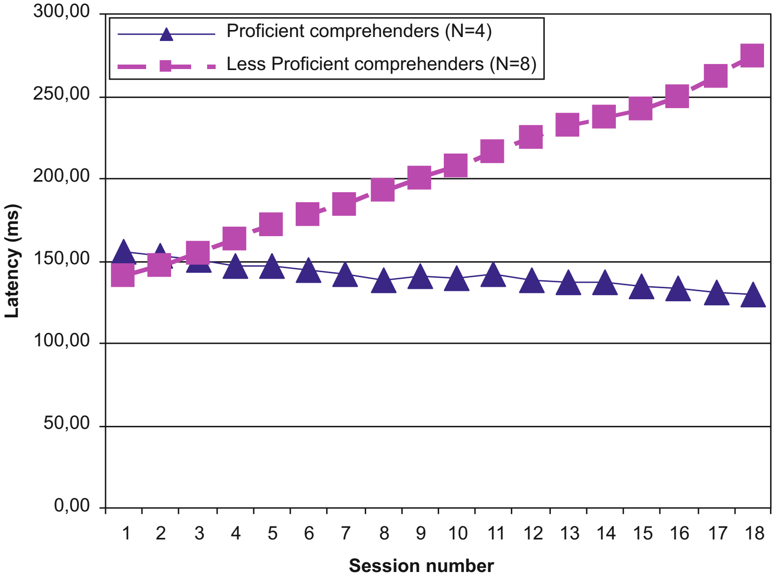

Fig. 1 Average reading rate development per letter during training (N = 12)

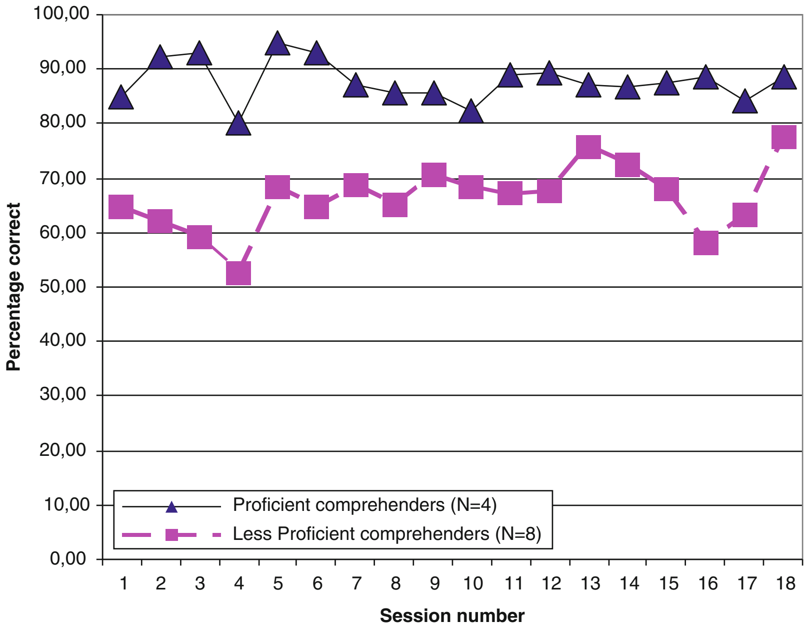

Fig. 2 Average comprehension development during training (N = 12)

Table 1 Mean reading rate per letter (milliseconds) on the self-paced and fast-paced tests before and after training. Proficient comprehenders (N = 4)

Mean reading rates per letter (milliseconds)				
Test		M	SD	*t*-test
Self-paced				
	Pretest	163.53	29.09	
	Posttest	138.27	46.25	ns
Fast-paced				
	Pretest	163.53	29.09	
	Posttest	98.78	33.57	0.79*

ns no significant difference between the pre- and the post-test
*$p = 0.06$

Table 2 Mean comprehension on the self-paced and fast-paced tests before and after training. Proficient comprehenders (N = 4)

Mean comprehension percentage				
Test		M	SD	*t*-test
Self-paced				
	Pretest	94	7.65	
	Posttest	88	4.61	ns
Fast-paced				
	Pretest	88	10.32	
	Posttest	86	12	ns

Ns no significant difference between the pre- and the post-test

Pre- and Post-test

To establish whether training had an effect on self-paced routine reading speed (unaccelerated reading) and comprehension, we compared the self-paced reading performance before and after the training, in the first and last sessions of the total of 20 sessions of the program. Finally, to establish whether training had an effect on fast-paced reading speed (accelerated reading) and comprehension, we also tested fast-paced reading and comprehension before and after the training in the first and last sessions of the program. As can be seen in Table 1, the proficient comprehenders improved in the fast paced reading condition. The differences after training were marginally significant ($T = 0.79$; $p = 0.06$). The difference between pre- and post-tests in self-paced reading was insignificant ($t = 1.1$; $p = 0.32$). The suggested differences in reading comprehension in both conditions were insignificant (see Table 2).

For the group of less proficient comprehenders, self-paced reading comprehension significantly improved after training ($t = 0.9$; $p = 0.05$). The suggested difference in reading speed between the pre and post self-paced reading conditions was

Table 3 Mean reading rate per letter (milliseconds) on the self-paced and fast-paced tests before and after training. Less proficient comprehenders (N = 8)

Mean reading rates per letter (milliseconds)				
Test		M	SD	*t*-test
Self-paced				
	Pretest	156.86	59.02	
	Postest	159.59	47.09	ns
Fast-paced				
	Pretest	156.86	59.02	
	Posttest	121.02	72.36	ns

ns no significant difference between the pre- and the post-test

Table 4 Mean comprehension on the self-paced and fast-paced tests before and after training. Less proficient comprehenders (N = 8)

Mean comprehension percentage				
Test		M	SD	*t*-test
Self-paced				
	Pretest	73.38	19.76	
	Posttest	90.00	7.09	0.90**
Fast-paced				
	Pretest	79.38	16.09	
	Posttest	84.13	5.94	ns

ns no significant difference between the pre- and the post-test
$^{**}p = 0.05$

insignificant. The means suggested that the fast-paced reading rate, and fast-paced reading comprehension slightly improved after training, but the differences between pre- and post-test were insignificant (See Tables 3 and 4).

6 Training Effects on Reading and Reading Related Tasks

Table 5 presents performance before and after training for all reading, spelling and cognitive tasks. Results of *t*-test analyses, between pre- and post-testing results of RAN-L, pseudoword reading time, and visual symbol search yielded significant differences. RAN-L and pseudoword reading times were shorter, and there were more correct answers in the symbol search task in the post-training measures compared to the pre-tests. No significant differences were found between pre- and post-training reading comprehension, orthographic choice, per-word reading time, and decoding errors in connected text (Table 5). The analysis of the total sample indicated that in comparison with normative scores, the mean score in spelling (orthographic choice task) was

Table 5 Training effects on reading: oral reading of pseudowords and connected text (N = 12)

	Pre-training		Post-training		
	M	SD	M	SD	*t*-test
RAN-Letters	29.49	7.79	25.36	5.15	3.66**
Pseudoword time (40 items) (in seconds)	62.28	21.00	53.31	15.55	2.25*
Number of Pseudoword errors (40 items)	5.41	4.08	5.00	4.7	ns
Orthographic choice task (correct responses out of 20 items)	13.67	3.47	13.83	3.35	ns
Per-word reading time of connected text (in seconds)	1.64	0.48	0.74	0.54	ns
Decoding errors in connected text	4.83	3.00	3.92	4.08	ns
Silent reading comprehension of connected text	7.15	0.88	5.70	1.77	ns
Symbol search (WISC-R, out of 60 items)	21.42	2.94	24.75	4.83	−2.2*

*$p < 0.05$
**$p < 0.01$

significantly lower than the mean in the test norms at pre- and post-test. The mean on the symbol search task was slightly lower than the norm mean in the pre-test, but above the test mean norms at the post-test. The rest of the mean scores were average at pre- and post-test.

7 Discussion

The present study examined the effects of the RAP on a small group of Spanish readers with dyslexia. The first research question was whether it is possible for dyslexic children to increase their comprehension levels when forced to read faster. Our data showed that dyslexic children could be pushed to read faster in a fast-paced reading test following training, although differences in reading speed were significant only for the proficient comprehenders. While these maintained their comprehension level, the less proficient comprehenders improved their comprehension ability following training in a self-paced reading test. These results provide some indication that reading acceleration training is also effective in Spanish and are in line with previous studies on the AP. The study by Snellings et al., 2009, showed that Dutch children with reading disabilities were able to increase their sentence reading rate with high comprehension levels when pushed to do so with accelerated reading training. In Hebrew, in a sample of adults with and without reading difficulties, Breznitz et al. (2013), showed that participants receiving accelerated training improved their reading fluency, as well as their reading comprehension scores, both during training and at a later follow-up assessment. Horowitz-Kraus et al. (2014) showed that English children with reading disability and typical readers improved

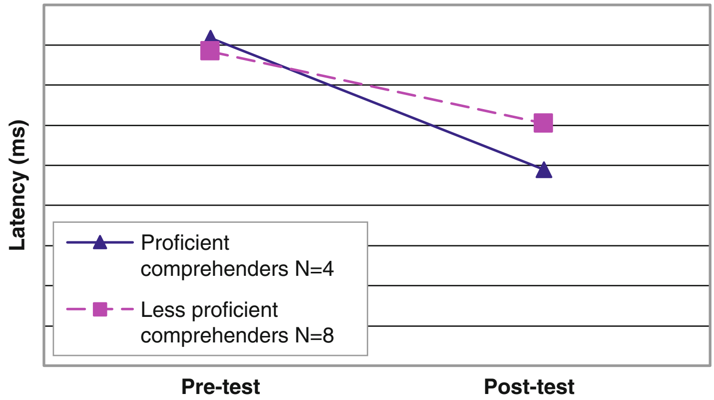

Fig. 3 Average reading rate in fast-paced tests

reading speed and reading comprehension with the accelerated reading training (also see results by Nagler et al., 2015 on German readers).

Together, these studies indicate that acceleration training was especially important for enabling children with reading difficulties to read fluently with high levels of comprehension. In the present study, participants could read faster in the post-test compared to the pre-test in the fast-paced condition (although this difference was significant only for proficient comprehenders), and they improved or maintained their reading comprehension level, providing evidence for the AP (see Figs. 3 and 4).

Results from the computerized training and from paper and pencil pre- and post-tests showed that comprehension was near ceiling for four of the participants, leaving little room for improvement. Nevertheless, these participants attained a faster reading rate in the fast-paced post-test with similar comprehension level. The result was even more striking for the other eight participants with lower reading comprehension levels, who managed to significantly improve comprehension in the self-paced condition following training (although reading rate did not improve). In fact, this group approached the level of comprehension of the good comprehenders (see Fig. 4). As in previous research (Horowitz-Kraus & Breznitz, 2014), performance gains for children with reading difficulties were larger than those of normally achieving peers because children with difficulties have more to gain. The results of this study demonstrate the importance of practice of reading under time constraints, as the less proficient comprehenders could reach almost the same level of reading comprehension of the proficient comprehenders. Constant practice may then be necessary in order to enable children with dyslexia to increase reading performance.

The second question was whether RAN, accuracy, reading rate, and reading comprehension in routine reading increase in children with dyslexia after training with the RAP. The present study found significant post-training gains in standardized reading tests such as RAN-Letters and pseudoword reading time. The study by Nagler et al. (2015) examining the RAP in German reading also reported significant

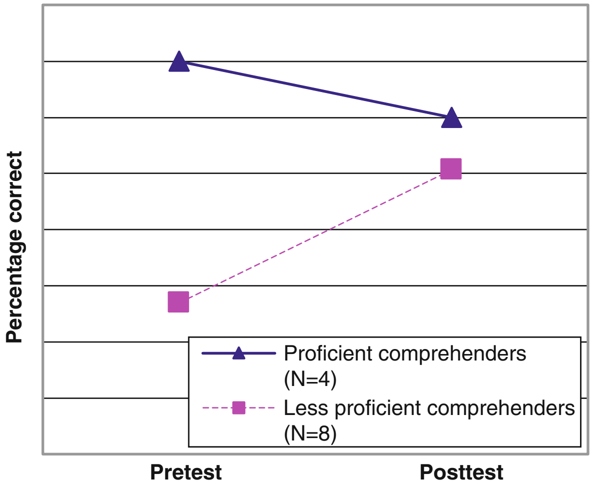

Fig. 4 Average comprehension in fast-paced tests

gains in fluency in reading of sentences in a standardized reading test. Horowitz-Kraus et al. (2014) also found transfer effects, after RAP training, on oral contextual reading speed and reading comprehension in the GORT-IV test, and on word and pseudoword reading in the TOWRE-II test, in a group of English speaking children with reading disabilities and typical readers.

Reading requires information processing under time constrains. Speed of information processing is a crucial factor in fluent reading. The faster reading rates induced by the RAP are supposed to train the dyslexic brain to process information at a faster rate that is normally attempted and improve *speed of processing* (see the study by Horowitz-Kraus & Breznitz, 2014). The improvement of speed of processing, after accelerated reading training, might improve the performance on reading related task, as the ones tested in this study – RAN and pseudoword reading rate.

We would like to add that transfer effects to text reading comprehension and spelling (as tested in an Orthographic choice task) were not found in the present study. Several reasons could explain this finding. As far as comprehension is concerned, probably because the reading comprehension level of these children was high or average, there was little room for improvement. Also, reading comprehension is not easily assessed by a single instrument, as different comprehension tests vary in the type of tasks used and in the cognitive demands required (Cutting & Scarborough, 2006; López-Escribano, Elosúa, Gómez-Veiga, & García-Madruga 2013). In this sense, we have to point out that the RAP training format consisted of sentences with multiple choice questions, and the paper and pencil reading comprehension test, that we used, consisted in a connected text with open questions. Different test formats require different cognitive abilities, and training in one test format does not necessarily transfer easily to a different reading comprehension test format. It is possible that significantly more training is needed to improve comprehension, as reading comprehension is a very complex process.

The third question was whether the accelerated reading training might result in a possible increase of attention in tasks such as visual symbol search. Results from the symbol search task indicate significant improvements in the post-test. It is possible that the accelerated reading procedure affects the individual's attention by reducing distractibility in reading (Breznitz, 1988). This level of attention promoted in reading, may generalize to different tasks as the visual symbol search task. A previous study by Horowitz-Kraus and Breznitz, (2014) also found improvements in visual screening and error monitoring. However, a generalization of our finding does not seem appropriate. Whether children with dyslexia can profit from the RAP in terms of attention capacity will need to be clarified in future studies.

Overall, the current study provided preliminary evidence for positive effects of the RAP in Spanish – on reading rate in good comprehenders and on comprehension in poor comprehenders. Some effects of transfer were also evident in standardized tests of decoding rate, speed of verbal processing (RAN) and visual attention (Symbol Search).

8 Limitations and Future Research

Several limitations are evident here, including the small sample size, which limits the possibility of generalising the results. Another limitation of our study is the lack of a control group with a different training condition. Since spelling is also a difficulty for children with reading disabilities in Spanish, further research, on the AP, should move beyond the sentence level and investigate the effects of the RAP on other aspects of literacy skills.

A Spanish version of the RAP has been already developed to include not only sentences, but also words and paragraphs. This version is in the process of evaluation for children with dyslexia during the fourth and fifth grades. A unique aspect of this program is that it is organized by levels of language: most frequent words that contains the letter "b", sentences, and paragraphs that also include trained words with "b" (the letter "b" was selected because the [b] sound is also represented for the "v" letter and the words containing this sound are hard to spell for Spanish children with dyslexia. Other letters could be selected in next versions). We are in the process of examining the effects of accelerated reading on test measures of reading fluency (word and sentence) and spelling of frequent words with "b" collected at pre-test, mid-test, immediate and follow-up post-test. The goal is to train fluency and spelling of a set of selected words that are repeated during the training sessions.

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