Letter-speech sound learning in children with dyslexia

From behavioral research to clinical practice

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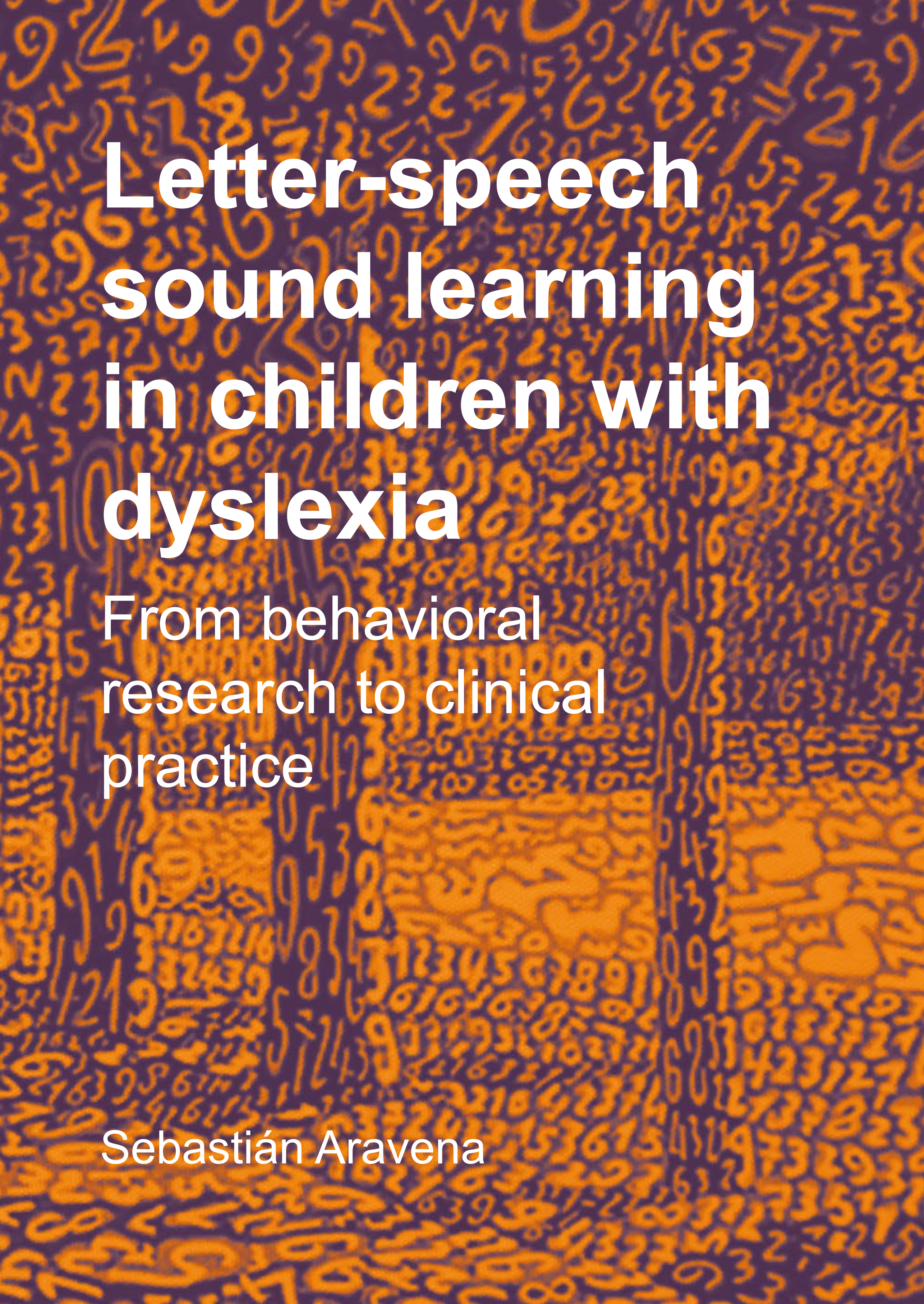

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Sebastián Aravena

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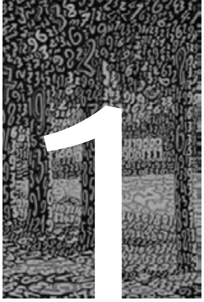


1

CHAPTER

General introduction

One day, long before starting my dissertation, I walked along the streets of Amsterdam and halted in front of a Moroccan Bank. My attention was caught by a tablet full of Arabic writings. For a few seconds I was surprised seeing some familiar numbers apparently hidden in between all the unfamiliar Arabic letters, but then it came to me that the numbers were just as Arabic as the letters. In my brain familiar symbols were only processed in a different way than unfamiliar ones. The myriad of previous encounters with Arabic numbers had adapted my brain to swiftly recognizing them. It was this process of familiarizing symbols that has fascinated me since that day, particularly when it comes to reading. In order to decipher words adequately, we must become highly familiar with the symbols that represent the sounds they are made up from, and, at the very beginning, any symbol looks just as outlandish as the Arabic writings did to me. Thus, at some point these symbols must get rid of their unfamiliarity, enabling fast recognition. How do we manage to do so, how does this attuning process bear upon reading acquisition, and is there a relation with developmental dyslexia?

With these questions in mind I started reading on the topic of letter-speech sound learning. At that moment the literature was scarce, but during the past few years this subject has received considerable attention (e.g., Blau, Van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Blomert, 2011; Fraga González et al., 2015; Hahn, Foxe, & Molholm, 2014; Jones, Kuiper, & Thierry, 2016; McNorgan, Randazzo-Wagner, & Booth, 2013; Mittag, Thesleff, Laasonen, & Kujala, 2013; Moll, Hasko, Groth, Bartling, & Schulte-Körne, 2016; van Atteveldt & Ansari, 2014; Žarić et al., 2015). The current dissertation aims at contributing to this emerging literature with a specific focus on letter-speech sound learning in children with developmental dyslexia. Whereas most of the studies so far within this area have been electrophysiological and neuroimaging studies, the current dissertation attempts to bridge the gap between this fundamental research and clinical practice by linking behavioral findings to assessment, prognostics and treatment. In this light we set up an innovative paradigm for studying letter-speech sound learning based on an artificial orthography. Before having a closer look at this paradigm we will first provide a general overview of the literature on developmental dyslexia and letter-speech sound learning.

Developmental dyslexia

As reading is a cultural invention, its cognitive underpinnings are relatively recent from an evolutionary perspective. It is therefore highly unlikely that our brain has specialized for reading by natural selection. We rather capitalize on more general networks to capacitate our cultural accomplishment (Anderson, 2010; Dehaene, 2009). As a consequence we need large amounts of instruction and practice to become a skilled reader. This in contrast to oral language acquisition, which arises naturally without considerable effort. Thus, learning to read is a complex process in which we manage to profoundly alternate our brain circuitry to facilitate fluent reading (Dehaene, 2009). From that perspective it is perhaps remarkable that so many of us are able to acquire this skill to such high degrees of proficiency. Nevertheless, a significant minority of individuals experiences major difficulties in mastering reading and spelling skills. When the automatic identification of written words is significantly impaired despite sensory integrity and normal educational opportunities, we generally apply the term developmental dyslexia, henceforth referred to as dyslexia (Lyon, Shaywitz, & Shaywitz, 2003; Snowling, 2012; Peterson & Pennington, 2015). Dyslexia is a learning disability of neurobiological origin with a genetic predisposition (Dehaene, 2009; Norton, Beach, & Gabrieli, 2015; Peterson & Pennington, 2015). It has been described in all writing systems, including non-alphabetical scripts (Goswami, 2007; Peterson & Pennington, 2012). However, as languages vary considerably in the consistency with which speech sounds are represented in orthographic symbols, some languages cause more difficulties to individuals with dyslexia than others (Landerl et al., 2013; Seymour, Aro, & Erskine, 2003; Ziegler & Goswami, 2005). More specifically, several studies demonstrate that consistent or transparent orthographies, such as Finnish, Spanish or Italian, are acquired more easily than inconsistent or opaque orthographies, such as Danish, French and particularly English (Landerl et al., 2013; Seymour et al., 2003).

Dyslexia affects approximately 3% to 10% of the population, depending on the exact criteria used for its assessment (Snowling, 2012). Despite being often labeled as a childhood disorder or a developmental lag, dyslexia is a persistent difficulty that does not remit with age or time (Bruck, 1998; Snowling, Muter, & Carroll, 2007). With the rise of the information society, in which written communication is essential, the burden of dyslexia on both individual and society is substantial.

Accordingly, dyslexia is associated with severe psychosocial, academic, and economic consequences (Herbers et al., 2012; Pape, Bjørngaard, Westin, Holmen, & Krokstad, 2011; UNESCO, 2005).

The dyslexic brain

Just as normal variability in reading skills, dyslexia is familial and moderately heritable (Carrion-Castillo, Franke, & Fisher, 2013; Pennington & Olson 2005). Dyslexia is found roughly in half of the children with first-degree family members who are diagnosed with dyslexia, which is far above its population prevalence (Scerri & Schulte-Körne, 2010). The disorder's hereditary nature is a strong cue for its neurobiological basis. The first neurobiological evidence was found in the late seventies when postmortem studies revealed anatomical differences in the brains of reading disabled individuals (Galaburda & Kemper, 1979). However, within the past few decades, neuroimaging methods, including magnetic resonance imaging, diffusion tensor imaging, and electrophysiology, have substantially boosted our knowledge of the neurobiology of dyslexia. With the aid of these techniques, studies have consistently revealed differences between children with dyslexia and typical readers (Dehaene, 2009; Norton et al., 2015; Peterson & Pennington, 2015; Richlan, 2012). More specifically, converging findings indicate functional and structural anomalies in two left hemisphere posterior brain systems: a temporoparietal system serving phonological processing and cross-modal integration of speech sounds, and an occipitotemporal system, including the so-called visual word form area, critical for instant word recognition and fluent reading (Norton et al., 2015; Paulesu et al., 2001; Richlan, 2012). Additionally, findings from recent studies demonstrate that these anomalies are already present before the onset of formal reading instruction and, therefore, are likely to reflect the cause of dyslexia rather than a consequence of reduced reading experience (Raschle, Chang, & Gaab, 2011; Vandermosten et al., 2015). Notwithstanding these findings, longitudinal studies suggest a prolonged interplay between both posterior brain systems and reading experience during the extended period in which we acquire fluent reading (Dehaene, 2009; Norton et al., 2015). It has been proposed that the early development of the temporoparietal system acts as a bootstrapping mechanism for the subsequent development of the occipitotemporal system (Blomert, 2011; Pugh et al., 2001; McCandliss & Nobel, 2003; Schlaggar & McCandliss, 2007).

Phonological processing deficit

Although numerous theories regarding the proximal cause of dyslexia have been proposed (Ramus & Ahissar, 2012), the most commonly accepted hypothesis is that it stems from a deficit in the phonological processing system (Dehaene, 2009; Vellutino, Fletcher, Snowling, & Scanlon, 2004). According to the phonological deficit hypothesis degraded representation, storage, or retrieval of speech sounds hinders the establishment of proper letter–speech sound mappings, which is the foundation of reading alphabetic languages, resulting in disfluent word recognition (Snowling, 1980; Vellutino, et al., 2004). A large body of literature substantiates that dyslexic readers typically experience difficulties on a wide array of phonological processing tasks (see Melby-Lervåg, Lyster, & Hulme, 2012 for a review). Phonological processing is commonly subdivided in three broad domains (Boets et al., 2010; Landerl et al., 2013; Ramus & Ahissar, 2012). The first of these is phonological awareness (PA) and refers to the ability to consciously identify and manipulate speech sounds and is usually assessed with tasks in which speech sounds have to be segmented, blended, replaced or deleted. An extensive body of research demonstrates that poor PA is one of the strongest correlates associated with reading and spelling disabilities (Melby-Lervåg et al., 2012).

The second domain is rapid automatized naming (RAN), which involves naming a series of familiar visually presented items, such as alphanumeric items, colors or objects, as quickly as possible (Denckla & Rudel, 1976). Poor achievement on RAN tasks is one of the strongest predictors of dyslexia (see Norton & Wolf, 2012, for a review). Findings indicate that 60% to 75% of individuals with a reading disability also exhibit a RAN deficit and that this deficit is present before reading instruction commences (Norton & Wolf, 2012).

The third domain that is commonly included under the umbrella of phonological processing, is verbal short-term memory (VSTM) (Mann & Liberman, 1984; Wagner & Muse, 2012). Typically, findings indicate that poor readers have shorter verbal memory spans on digit span tasks and nonword repetition tasks (Berninger et al., 2006; Georgiou, Das, & Hayward, 2008; Wagner & Muse, 2012).

Whether these three phonological domains are independent or share a common underlying factor has long been debated (e.g. Georgiou et al., 2008; McCallum et al., 2006; Ramus & Szenkovits, 2008; Vaessen, Gerretsen, & Blomert, 2009). An influential hypothesis is that phonological representations are degraded in individuals with dyslexia, reflecting a core phonological component (Elbro, Borstrom, & Petersen, 1998). Others have argued that it is the access to phonological representations rather than the representation itself that is hampered in dyslexia (Boets et al., 2013; Ramus & Szenkovits, 2008). A common view is that PA and VSTM rely on a core phonological component (Melby-Lervåg et al., 2012), whereas RAN constitutes an independent factor (Bowers & Ishaik, 2003; Wolf & Bowers, 1999). This double deficit hypothesis (Wolf & Bowers, 1999) claims that PA and RAN contribute separately to reading ability and that co-occurrence of these deficits results in the most severely impaired reading skills.

Although the phonological deficit hypothesis has been the most dominant explanatory theory of dyslexia over the past 30 years, its causal status continues to be debated (Blomert & Willems, 2010; Castles & Coltheart, 2004; Castles, Wilson, & Coltheart, 2011; Hulme, Snowling, Caravolas, & Carroll, 2005; Morais et al., 1979; Perfetti, Beck, Bell, & Hughes, 1987; Ziegler & Goswami, 2005). As phonological awareness improves during reading development and it is difficult to pinpoint the onset of reading acquisition in our highly literate society, separating causes from consequences is indeed an arduous task (Dehaene, 2009). More specifically, it has been argued that phonological processing skills may develop as a consequence rather than as a precursor of reading acquisition, and, in line with this proposal, there is still no convincing evidence that phonological awareness precedes and directly influences reading acquisition as is commonly assumed (Blomert & Willems, 2010; Castles & Coltheart, 2004; Castles, Coltheart, Wilson, Valpied, & Wedgwood, 2009; Morais, Cary, Alegria, & Bertelson, 1979; Morais & Kolinsky 2005; Perfetti, et al., 1987). This view is empirically supported by some studies with children at familial risk for dyslexia (Blomert & Willems, 2010; Castles et al, 2009). In one such study, Castles and colleagues (2009) found that 6 weeks of phonemic awareness training did not directly assist preliterate children in subsequently learning letter–sound correspondences. However, in support of a causal relation between phonological processing skills and reading, other studies found several indices of phonological competence, among which PA and RAN, measured before school age to be predictive of future reading skill (Lyytinen, Erskine, Hämäläinen, Torppa, & Ronimus, 2015; Maurer, Bucher, Brem, & Brandeis, 2003; Pennington & Lefly, 2001; Storch & Whitehurst, 2002; Torppa, Lyytinen, Erskine, Eklund, & Lyytinen, 2010).

An important assumption of the phonological theory of dyslexia is that the phonological impairments hinder the establishment of proper letter–speech sound mappings, which is the foundation of reading in alphabetic languages, resulting in disfluent word recognition. The theory thus provides a straightforward link between the underlying cognitive problem and the behavioral manifestation of dyslexia. Despite its presumed importance as a link between a phonological deficit and the reading failure that characterizes dyslexia, etiological research has focused primarily on identifying and understanding the specific shortcomings in phonological processing. In contrast, letter–speech sound binding itself, has long received little attention from an empirical point of view. This dearth of research has recently been counterbalanced by an increasing number of studies addressing the formation of letter-speech sound correspondences as an important etiological factor in dyslexia (Blau et al., 2009; Blomert, 2011; Fraga González et al., 2015; Froyen, Willems, & Blomert, 2011; Hahn et al., 2014; Jones, Branigan, Parra, & Logie, 2013; Jones et al., 2016; Kronschnabel, Brem, Maurer, Brandeis, 2014; McNorgan et al., 2013; Mittag et al., 2013; Moll et al, 2016; van Atteveldt & Ansari, 2014; Wallace, 2009; Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012; Žarić et al., 2014; Žarić et al., 2015; Žarić et al., 2016).

Letter-speech sound learning

As written language is intended to capture oral language so that it can be preserved and dispersed independently of the speaker, associating auditory information with visual information is a critical step in becoming a skilled reader. Indeed, in alphabetic languages, learning to read fundamentally entails linking speech sounds to letters (Ehri, 2005; Share, 1995; Snowling, 2000), a process that is referred to as mastering the alphabetic principle (Liberman, Shankweiler, & Liberman, 1989). Therefore, in the initial stages of formal education there is a central focus on teaching letters. Accordingly, a large body of research has shown that letter knowledge at the beginning of literacy instruction is a strong predictor of later literacy skills (Caravolas et al., 2012; Foulin, 2005; Hulme, Nash, Gooch, Lervåg, & Snowling, 2015). Most children acquire the knowledge of letter–speech sound associations within a year of formal reading instruction (Blomert & Vaessen, 2009), but it seems that several more years of education and experience are needed for these associations to become fully integrated in the sense that seeing a letter automatically and instantaneously co-activates the paired auditory information (Blomert & Vaessen, 2009; Froyen, Bonte, van Atteveldt, & Blomert, 2009). Importantly, it is assumed that fluent reading can only come about when letter-speech sound mappings have become highly overlearned (Blomert, 2011; Holloway, van Atteveldt, Blomert, & Ansari, 2013; McNorgan et al., 2013).

A closer look at electrophysiological and neuroimaging data gives insight into the protracted development of letter-speech sound integration. Using a mismatch negativity paradigm, Froyen and colleagues (2008, 2009) demonstrated that after 1 year of reading instruction, beginning readers did not show any early neural signs of letter–speech sound integration. Moreover, they found that even after 4 years of reading instruction, the integration was still not ‘‘adult-like’’. In addition, by measuring response latencies of letter–speech sound matching, Blomert and Vaessen (2009) showed that processing speed of these associations increased systematically over the full range of primary school grades despite ceiling performance on accuracy measures from first grade onward (see Figure 1).

The overall results from the ERP studies by Froyen and collaborators (2008, 2009), complemented by findings from related functional magnetic resonance imaging (fMRI) studies (Blau, van Atteveldt, Formisano, Goebel, & Blomert, 2008; van Atteveldt, Formisano, Goebel, & Blomert, 2004; van Atteveldt, Formisano, Blomert, & Goebel, 2007) have thus led to a renewed perspective on the formation of correspondences between letters and speech sounds according to which learning letter-speech sound associations is just a first step in a long tuning process that leads to well-integrated audiovisual units in the brain. It is this tuning process that determines whether someone is able to effectively use the learned correspondences in fluent reading. In other words, there is an important difference between knowing letter-speech sound correspondences and having them stored as well-integrated audio-visual units.

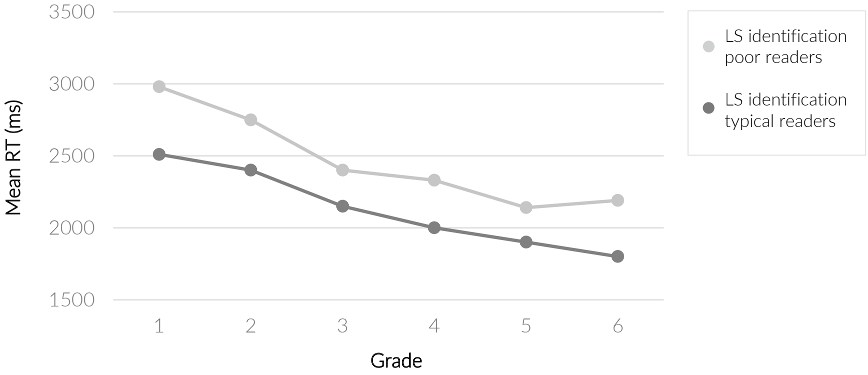


Figure 1 Development of letter-speech sound integration in primary school: identification reaction time corrected for baseline RT. Legend: LS=letter-speech sound; n=365 poor readers, n=1972 typical readers. Source: Blomert and Vaessen, 2009.

Another important insight from research within this domain is that the audiovisual integration of letters and speech sounds is weaker in children with dyslexia, suggesting that reading difficulties may partly arise from a fundamental letter-speech sound integration deficit (Blau et al., 2009; Blomert, 2011; Fraga González et al., 2015; Froyen et al., 2011; Hahn et al., 2014; Jones et al., 2013; Jones et al., 2016; Kronschnabel et al., 2014; McNorgan et al., 2013; Mittag et al., 2013; Moll et al., 2016; van Atteveldt & Ansari, 2014; Wallace, 2009; Widmann et al., 2012; Žarić et al., 2014; Žarić et al., 2015).

Impaired letter-speech sound learning in dyslexia

Evidence for disrupted letter-speech sound learning in dyslexia mainly comes from brain potential and neuroimaging research demonstrating that in dyslexia the activity of temporoparietal brain areas is reduced in response to letter-speech sound associations (Blau et al., 2010; Blomert, 2011; McNorgan et al., 2013; Wallace, 2009). It is important to note that these deviant brain responses were found despite adequate knowledge of the concerning letter-speech sound correspondences, indicating that it is the actual integration that is hampered (Blau et al., 2010; Froyen et al., 2009). Additionally, the degree of activation of temporoparietal areas was found to correlate with the speed of performance in letter-speech sound matching tasks (Blau et al., 2010). In further support of the view that a letter-speech sound binding deficit is a key factor in dyslexia, brain studies with preliterate children at familial risk for dyslexia indicate that deficits in temporoparietal processing predict reading disabilities (Molfese, 2000; Raschle et al., 2013).

Blomert (2011) hypothesized that a specific orthographic–phonological binding deficit may not only act as a proximal cause for reading impairments in dyslexia, but may also explain the persistent lack of reading fluency in individuals diagnosed with dyslexia. This is important because the influential phonological deficit hypothesis fails to elucidate why disfluent reading is the most notorious characteristic of dyslexia and why phonological training has little impact on reading fluency (Biancarosa & Snow, 2004; Blomert, 2011). In support of Blomert’s view, Žarić and colleagues (2014) found that reduced neural integration of letter-speech sound correspondences in children diagnosed with dyslexia correlates with individual differences in reading fluency. Moreover, recent findings indicate that children with dyslexia show substantial gains in both letter-speech sound integration and reading skills, including reading fluency, in response to an intensive training of letter-speech sound mappings (Fraga González et al., 2015; Žarić et al., 2015). The children with dyslexia improved their reading skills at a faster rate than typical readers and waiting-list controls (Fraga González et al., 2015; Žarić et al., 2015). Interestingly, Fraga González and his collaborators found that reading fluency gains were related to baseline differences in letter-speech sound mapping fluency in the waiting-list group, but not in the training group. It thus seems that by intensively training letter-speech sound integration children with dyslexia are able to overcome their initial mapping deficiency and are able to improve their reading fluency (Fraga González et al., 2015).

It is important to note, that most of the brain potential and neuroimaging research done so far on the topic of letter-speech sound learning, involves Dutch children. In a recent fMRI study with English reading-disabled adults the neural correlates of multisensory letter-speech sound integration were associated with orthographic depth (Holloway et al., 2013). More specifically, they found that letter-speech sound correspondences were less integrated in English readers than in Dutch readers. As all studies reported in the current dissertation are based on a transparent orthography (i.e., Dutch or artificial orthography), we need to be cautious in generalizing the associated findings to more opaque orthographies.

In contrast to neurobiological evidence, behavioral evidence for deficits in letter-speech sound learning in dyslexia remains scarce. A few studies have reported that children with dyslexia have difficulties mastering letter-speech sound correspondences (Blomert & Vaessen 2009; Fox, 1994; Siegel & Faux, 1989; Snowling, 1980), but the actual process of learning these mappings was not directly addressed. Interestingly, Blomert and Willems (2010) found that a letter–speech sound learning problem was already present in preschool children at familial risk for dyslexia. These at-risk children did not profit from a 10-week letter–speech sound training, whereas the controls improved significantly. This indicates that although the neural integration of letter–speech sound associations is a gradual process that takes many years to fulfill, differences between dyslexic and typical readers may already be detected during an initial phase of this process.

Assessment of dyslexia

In most countries diagnostic assessment of dyslexia consists of a combination of reading and writing tasks along with a set of phonological tasks and some general cognitive measures, such as intelligence and vocabulary (Marzola & Shepherd, 2005). In order to find evidence for a core phonological deficit, the three main areas of phonological processing are typically explored: phonological awareness, rapid automatized naming, and verbal working memory (Boets et al., 2010; Ramus & Ahissar, 2012). For years, this trichonomic approach predominated diagnostic assessment in the Netherlands as well. However, the findings during recent years have led to the inclusion of a letter-speech sound integration measure (Blomert, 2006). Accordingly, Dutch health-care protocol prescribes that children are diagnosed with severe dyslexia when they meet all of the following four criteria: (1)

either word reading speed is at least 1.5 standard deviations (SD) below average or, word reading speed is at least 1 SD below average together with spelling skills of at least 1.5 SD below average; (2) performance on at least two out of six administered phonology-related tasks (i.e., grapheme–phoneme identification task accuracy and speed, phoneme deletion accuracy and speed, and rapid naming of numbers and letters) is at least 1.5 standard deviations below average; (3) there are no indications of alternative or co-morbid disorders; and (4) response to school-provided intervention was poor. With respect to this last criterion, the Dutch educational system utilizes a variant of the common Response to Intervention (RTI) framework (Fuchs & Fuchs, 2006). RTI is an approach in which a tutor provides a pupil with progressively intense and individualized tiers of instruction with the aim of finding the best possible way to educate children and of identifying children with learning disabilities (Denton, 2012; Fuchs & Fuchs, 2006; Grigorenko, 2009; Gustafson, Svensson, & Fälth, 2014). Pupils who do not respond to Tier 1 receive more intensive and individualized instruction within Tier 2, and those who are unresponsive to Tier 2 proceed with even more rigorous instruction within Tier 3. Depending on the educational system, the framework is sometimes complemented by a fourth tier, which consists of placement in special education or referral to assessment and therapy within the health care system. In the Netherlands, pupils who do not benefit from Tier 3 intervention are referred to clinical assessment.

In the current dissertation, selection of the dyslexic group was based on the abovementioned criteria for severe dyslexia in the Dutch health care system (Blomert, 2006), implying that children had a severe and persisting reading (and spelling) problem in combination with a phonological deficit, and in the absence of co-morbid disorders. Inclusion of a causal factor (i.e., a phonological deficit) in the diagnosis provides the possibility to select a homogeneous sample, promoting generalization and replication of results (Torgesen et al., 1999).

Treatment of dyslexia

Being unable to read has a negative impact on an individual's academic and labor life as well as on their well-being. Undiagnosed or untreated dyslexia in adults is associated with low self-esteem, anxiety, depression, social isolation, and increased risk of developing psychopathological problems (Esser, Wyschkon, & Schmidt, 2002; Ruijssenaars, de Haan, Mijs, & Harinck, 2008), and the outlines of these problems are already manifest during primary school (Ingesson, 2007; Maughan & Carroll, 2006). Hence, the need for adequate evidence-based treatment programs is obvious.

There is ample evidence that specialized intervention is effective in ameliorating reading and spelling proficiency of children with dyslexia. The most effective treatment programs include systematic phonics instruction along with decoding strategies, and the application of these skills in reading and writing activities (Galuschka, Ise, Krick, & Schulte-Körne, 2014; Scammacca, Roberts, Vaughn, & Stuebing, 2015; Singleton, 2009). Phonics instruction typically combines elements of reading fluency training, like repeated reading practice, and phonemic awareness training. Meta-analytic research suggests that interventions that focus on reading fluency or phonemic awareness training in isolation are ineffective (Galuschka et al., 2014; Scammacca et al., 2015). In a series of studies within the Netherlands, including randomized controlled trials, Tijms and his collaborators showed that a Dutch phonics instruction treatment program produced significant long-lasting improvements in children diagnosed with dyslexia (Fraga González, 2015; Tijms, Hoeks, Paulussen-Hoogeboom, & Smolenaars, 2003; Tijms & Hoeks, 2005; Tijms, 2011). From a more formal didactic point of view, evidence indicates that successful interventions are intense, systematic, and explicit (Shaywitz, Morris, & Shaywitz, 2008; Snowling, 2012). Indeed, specialized intervention is usually extensive with an average duration ranging from 50 to 80 hours (Torgesen, 2005).

Unfortunately, not all dyslexic readers benefit to the same extent from intervention and there is a substantial amount of non-responders as well (Galuschka et al., 2014, Singleton, 2009; Torgesen, 2005). More specifically, reading fluency is less susceptible to intervention than reading accuracy (Shaywitz et al., 2008; Lyon & Moats, 1997; Torgesen, 2005). Therefore, gaining more insight into factors that can help improving reading fluency, is one of the central issues of contemporary research on reading (Kame’enui & Simmons, 2001; Samuels, 2006; Rasinski, 2012). In view of the evidence discussed above, intensive training of letter-speech sound integration in children with dyslexia has been identified as a promising candidate for improving reading fluency (e.g., Fraga González et al., 2015).

A new paradigm

In an effort to expand our knowledge of letter-speech sound learning and its relation to dyslexia we developed a paradigm with two innovative characteristics. First, the paradigm features a challenging computer game as an agent for learning letter-speech sound correspondences, and, second, it highlights letter-speech sound pairings within an artificial orthography as learning material. The computer game requires children to match speech sounds to their corresponding orthographic representations as fast as possible. Correct associations lead to success in the game, whereas incorrect associations are penalized.

Utilizing a computer game enables us to focus on spontaneous associative learning from exposure and implicit feedback rather than on training by explicit instruction. By this means the learning process approximates letter-speech sound learning as it occurs naturally. Moreover, it provides the opportunity to measure the capability of mastering new letter-speech sound correspondences, without interference from more general factors related to instruction, such as intelligence, verbal comprehension, or attention.

The great advantage of applying an artificial orthography is that there are no a-priori differences in exposure to the stimuli, providing a unique opportunity to study letter-speech sound learning in relation to literacy and phonological processing, without concerns about reciprocity between these factors. The script is artificial in the sense that unfamiliar letters (Hebrew) are used to transcribe native speech sounds.

Our goal was to relate our research findings to educational and clinical practice and to assess the diagnostic and prognostic value of associative letter-speech sound learning within an artificial orthography. Accordingly, we set up a dynamic assessment (DA) based on the aforementioned game. This DA consists of a 20-minute training aimed at learning eight basic letter-speech sound correspondences, followed by a short assessment of both mastery of the correspondences and word reading ability in this unfamiliar script. The advantage of DA over traditional static assessment is that it focuses on learning potential rather than on learning outcome (Grigorenko, 2009; Gustafson et al., 2014). A typical DA procedure requires the pupil to engage in a training in which feedback is provided. The effect of training is then used to estimate the pupils' learning potential. There is ample evidence that this kind of process-oriented testing better predicts future learning than conventional testing within various academic domains, including reading skill (Caffrey, Fuchs, & Fuchs, 2008; Fuchs, Compton, Fuchs, Bouton, & Caffrey, 2011; Grigorenko & Sternberg, 1998; Gustafson et al., 2014; Jeltova et al., 2007; Spector, 1992). Note, that our DA is different from most approaches to DA (Grigorenko, 2009; Grigorenko & Sternberg, 1998), as it does not involve explicit instruction but capitalizes on associative learning.

Outline

The research presented in the current dissertation aims at further elucidating the nature of letter–speech sound learning and its relation to phonological processing and reading development. More specifically, it attempts to bridge the gap between fundamental research and clinical practice by linking behavioral findings to assessment, prognostics and treatment.

Chapter 2 consists of a theoretical review of reading fluency and its remediation in children diagnosed with dyslexia. It provides an overview of research regarding fluent and hampered reading, with a specific focus on letter-speech sound learning and on gaming as a means to invoke massive repetitive training of letter-speech sound correspondences.

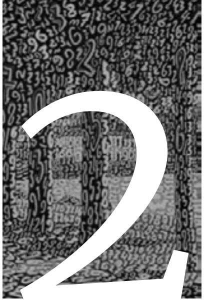
In Chapter 3 we present a study in which we examined the influence of instructional approach on the initial learning of letter–speech sound correspondences. We were specifically interested in the role of implicit training techniques as a means to induce automation of letter–speech sound processing. We assigned children diagnosed with dyslexia and typical developing readers to one of three different training conditions: (a) explicit instruction, (b) implicit associative learning within a computer game environment, or (c) a combination of (a) and (b) in which explicit instruction was followed by implicit learning.

In Chapter 4 we discuss a study in which we examined the learning of letter-speech sound correspondences within an artificial script and performed an experimental analysis of letter-speech sound learning in dyslexic and typical readers vis-à-vis phonological awareness, rapid automatized naming, reading, and spelling. We were specifically interested in the potential of our dynamic assessment to predict individual differences in reading and spelling skill and to differentiate between dyslexic readers and typical readers. Furthermore, we wanted to fit the results obtained into the common framework of dyslexia by examining how letter-speech learning relates to phonological awareness and rapid naming and by comparing their contributions in predicting individual differences in reading and spelling abilities.

Chapter 5 presents a study in which we explored the value of our dynamic test for predicting responsiveness to reading intervention for children diagnosed with dyslexia. The participating children engaged in specialized intervention during approximately 10 months. We tested their reading and spelling abilities before and after intervention and related these to the scores on our DA, as well as to the scores on a phonological awareness task and an alphanumeric rapid naming task.

In Chapter 6 we focus on letter-speech sound learning in kindergarten children. More specifically, we present a study in which we examined whether, compared to their typical-risk peers, children at risk for dyslexia performed more poorly on learning new letter-speech sound correspondences before the onset of reading instruction. Furthermore, we investigated whether our dynamic assessment was able to predict word reading fluency two years later, at the end of Grade 2.

In Chapter 7 we summarize and discuss the research reported in the previous chapters and reflect on the various findings from a broader perspective, as well as on their implications for theory and educational and clinical practice.



2

CHAPTER

Innovative developments in the role of letter-speech sound learning and repetitive exposure in enhancing reading fluency

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When a reporter asked former world chess champion José Capablanca, often referred to as a candidate for the greatest chess player of all time, how many moves ahead he looked while playing, Capablanca replied: "Only one, but it's always the right one". Obviously these words were intended somewhat hilariously and suit the grandeur of a chess champion. However, in the light of modern science these same words capture astonishingly well what is currently known about what distinguishes experts from novices within various domains, namely, that it is fast automatized perceptual recognition that potentiates their superior skill. In reading this is not different. Skilled readers develop a form of visual expertise that allows them to process print with remarkable efficiency, i.e., the reading rate of a skilled reader surpasses the rate of typical speech. Even words of more than 15-20 characters can be identified within a fraction of a second (Nazir & Huckauf, 2008).

Most people can become highly proficient in reading without considerable effort. Nevertheless, a substantial part of the population experiences major difficulties in mastering reading and spelling skills. When these difficulties occur despite sensory integrity, normal intelligence, and educational opportunity, they are generally designated as dyslexia (Shaywitz, Morris, & Shaywitz, 2008). In transparent orthographies, like Spanish or Finnish and to a lesser extent Dutch, dyslexia is primarily characterized by poor reading fluency (Landerl, Wimmer, & Frith, 1997; Ziegler, Perry, My-Wyatt, Ladner, & Schulte-Korne, 2003).

Although specialized treatment programs are effective in alleviating the reading and spelling difficulties of individuals with dyslexia (Elliot, Davidson, & Lewin, 2007; Fletcher, Lyon, Fuchs, & Barnes, 2007; Lovett, Barron, & Benson, 2003; Tijms & Hoeks, 2005; Vellutino, Scanlon, Small, & Fanuele, 2006), these treatment gains hardly ever generalize substantially to fluent reading (Shaywitz et al., 2008; Torgesen, 2005). This is problematic because a lack of reading fluency is assumed to hinder reading comprehension (Samuels, 2002). Hence, identification of educational principles that could enhance reading fluency is one of the central issues of contemporary research on reading.

In this chapter we will engage in a theoretical quest for ways to ameliorate reading fluency in individuals with dyslexia. By this means we will provide an overview of research regarding fluent reading and disabled reading, with a special focus on cognitive neuroscience. The rapid development of functional neuroimaging techniques has given researchers unprecedented access to the behaving brain and there is growing optimism that cognitive neuroscience can make a meaningful contribution to education. In fact there are studies that illustrate the promise of neuroscience by showing how the brain responds to training. For example, Shaywitz and colleagues (2004) found that the activity in the dyslexic brain, which is usually atypical, approximates normal activity after specialized treatment. Moreover, brain imaging has indicated a target (an area within the posterior ventral region of the brain) for fluency-oriented intervention. Additionally, the place-based reporting scheme of neuroimaging has indicated that there are similarities between fluent reading and other forms of high proficiency of skill on a neural level. In our quest we will therefore also attend to the paradigm of expert learning and return to Capablanca and the science behind his self-contemplation.

A final contribution from neuroscience to education comes from connectionist models of reading. These models complement behavioral and neuroimaging studies. We will end this chapter by putting forward some promising new directions for treatment, with an emphasis on fluency-oriented educational principles. As an example we will present an educational computer game, called LexyLink, which we developed in our laboratory and which we are currently testing.

Dyslexia

The ability to read and write allows people to transcend their confinement to time and space, and therefore is the central focus of attention in education. Nevertheless, as mentioned, a substantial part of the population experiences major difficulties in mastering reading and spelling skills. The term dyslexia typically is invoked when these difficulties are unexpected in relation to other cognitive abilities and adequate education (Shaywitz, Morris, & Shaywitz, 2008).

Dyslexia is considered to stem from a deficit in the phonological processing system, which disrupts the development of phonemic-graphemic associations (Shaywitz et al., 2008; Sprenger-Charolles, Colé, & Serniclaes, 2006). A subtle neurological defect that is associated with a genetic predisposition, is assumed to be the underlying factor (Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006; Fisher & Francks, 2006; McGrath, Smith, & Pennington, 2006). Recent work suggests that genetic disruptions interfere with neuronal migration, leading to atypical neural organization (Burbridge et al., 2008; Galaburda et al., 2006; Meng et al., 2005; Velayos-Baeza, Toma, Paracchini & Monaco, 2008).

Dyslexia has a relatively high prevalence and has been described in all writing systems, including logographic ones (Goswami, 2007). Prevalence estimates typically range from 3% to 10% of the population (Eden & Moats, 2002), with a slight preponderance of males over females (Rutter et al., 2004). Despite being often labeled as a childhood disorder or a developmental lag, dyslexia is a persistent difficulty, which must be recognized and addressed early (Shaywitz et al., 2008). In adults, dyslexia is associated with low self-esteem, anxiety, depression, social isolation, and increased risk of developing psychopathological problems (Esser, Wyschkon, & Schmidt, 2002; Ruijssenaars, De Haan, Mijs, & Harinck, 2008). Up to a certain extent such problems are already manifest during primary school (Ingesson, 2007; Maughan & Carroll, 2006). With the rise of the information society, in which written communication is essential, the burden of dyslexia on both individual and society will be increasingly high. Hence, a focus on adequate treatment for dyslexia is indispensable.

Treatment of dyslexia

As dyslexia is the most common and the most carefully studied of the learning disabilities, significant progress has been made in understanding the cognitive basis of dyslexia and in using this knowledge to ameliorate instructional practices (Shaywitz et al., 2008). It seems that typical instructional practices within the public school as well as facilities within special education are able to stabilize the degree of reading failure of pupils with dyslexia, but are not proficient in normalizing their reading skills (Torgesen, 2005). Therefore, most children with dyslexia have to rely on specialized treatment programs.

Extensive literature on prevention and intervention of dyslexia indicates that treatment can be successful, and sheds light on which ingredients are responsible for that success. Positive results have been reported in studies evaluating phonologically based prevention and intervention methods (Elliot et al., 2007; Fletcher et al., 2007; Fuchs & Fuchs, 2006; Lovett et al., 2003; Tijms & Hoeks, 2005;

Vellutino et al., 2006). It seems that prevention programs that explicitly focus on phonemic awareness, phonics, and semantics reduce the risk of developing reading difficulties (Fuchs & Fuchs, 2005; Vellutino et al., 2006). Similar ingredients are associated with positive outcomes in intervention methods (Elliot et al., 2007; Fletcher et al., 2007; Hatcher, Hulme, & Snowling, 2004). The most effective treatment programs include training in phonetic awareness that is explicitly linked with systematic instruction in reading (Elliot et al., 2007; Hatcher, Hulme, & Ellis, 1994). A supplementary focus on teaching children metacognitive strategies to assist in word identification appears to be of additional value (Lovett et al., 2003). From a more formal didactic point of view, evidence indicates that successful interventions are intense, systematic, and explicit (Shaywitz et al., 2008). Indeed, specialized intervention is usually extensive with an average duration ranging predominantly from 50 to 80 hours (Torgesen, 2005).

Although phonology-based treatment evaluations revealed positive effects, the durability of these effects after treatment is stressed in a few studies only (Hatcher et al., 1994; Tijms, Hoeks, Paulussen-Hoogeboom, & Smolenaars, 2003; Torgesen et al., 2001). In an extensive study Tijms et al. (2003) showed that a phonology-based treatment program for the Dutch language produced long-lasting effects, i.e., despite a slight decline in spelling proficiency after the first year, the participants maintained their functional levels of reading and spelling.

Notwithstanding the positive outcomes associated with phonology-based interventions, one notable result is that reading rate is less susceptible to intervention than reading accuracy (Shaywitz et al., 2008; Lyon & Moats, 1997; Torgesen, 2005). However, it seems that, as opposed to reading accuracy, reading rate continues to develop after termination of specialized treatment (Tijms, 2007). Identification of instructional elements that are capable of improving reading rate, and by that reading fluency, is one of the central issues of contemporary research on reading (Kame'enui & Simmons, 2001; Kuhn & Stahl, 2003; Lyon & Moats, 1997; Shaywitz et al., 2008; Torgesen, 2005).

What about fluency?

Traditionally, reading fluency has received far less attention than reading accuracy and has been frequently nominated as the ‘neglected’ aspect of reading (Allington, 1983; Pikulski & Chard, 2005). In recent years however, this topic has gained the interest of both researchers and practitioners (e.g. Kuhn & Schwanenflugel, 2007), with special attention for the dynamics that lead to reading fluency (Kuhn & Stahl, 2003).

There are several definitions of reading fluency mostly stressing accuracy, rate, and prosody as the key elements (Hudson, Mercer, & Lane, 2000; Kuhn & Stahl, 2003; Torgesen & Hudson, 2006). Fluency is usually associated with effortlessness and is hence characterized by the ability to maintain the reading performance for long periods of time, to retain the skill after long periods without practice, and to generalize across texts (Hudson, Lane, & Pullen, 2005). The effortlessness also leads to an inability to suppress reading (Everatt et al., 1999). Even when skilled readers are expressly asked to pay attention solely to trivial aspects of words (e.g. color or ink), they appear to be unable to suppress reading (Noble & McCandliss, 2005). Sprenger-Charolles, Colé, and Serniclaes (2006) appropriately refer to this phenomenon as the written-word identification “reflex”.

A lack of reading fluency conversely is marked by slow, hesitant, and laborious reading, which is assumed to hinder reading comprehension (Samuels, 2002). Indeed, a correlation between fluency and reading comprehension is clearly established (Johns, 1993; Pinnell et al., 1995). The putative causality of this correlation was elucidated in a seminal article by LaBerge and Samuels (1974). They stated that attention expended upon one activity is, inevitable, attention unavailable for another. Since comprehension depends on meta-cognitive processes, it cannot be automatized. It is therefore necessary to automatize the decoding aspect of reading in order to free capacity for the meta-cognitive process of constructing meaning. When failing to do so, one must constantly alternate attention between the two processes.

A central question regarding fluency is how it originates within reading development. Ehri (2002) describes reading development as a stage-like process ranging from being a non-reader to the point where words are recognized effortlessly. Through a thorough analysis of their structure, words become sight words, in the sense that they belong to the ‘instant recognition repertoire’ of the reader. In her model, Ehri identifies four developmental stages: pre-alphabetic, partial alphabetic, full alphabetic, and consolidated alphabetic. In the pre-alphabetic stage the beginning reader has no insight into the alphabetic principle yet, and thus uses visual characteristics or clues from the context to identify printed words. When the reader starts to relate sounds to specific easily identifiable parts of the word, mostly at the beginning and endings, it has reached the partial alphabetic stage. The full alphabetic stage is characterized by the ability to attend consciously to all of the sounds within a word. This ability makes it possible to decode words that are presented for the first time. In the final stage, the consolidated alphabetic stage, repeated exposure to print leads to a chunking process in which larger patterns of letters are recognized, facilitating more rapid identification and processing of words during reading.

Chall (1996) also relates fluency to a theoretical framework in which reading proficiency proceeds through developmental stages. She particularly stresses the importance of gaining familiarity with sound-symbol correspondences, which leads to a stage in which the reader is not learning new skills, but confirming what is already known. Chall’s model partly coincides with Ehri’s, but also focuses on reading comprehension in addition to decoding.

The view of reading development as a series of qualitatively different stages through which learners proceed, does not necessarily mean that the reader goes through one stage at the time. In fact it is plausible that this development proceeds in an item based fashion, in which for some words the reader must rely heavily on effortful decoding, while other words are already processed automatically (Share, 1995). Perfetti (1992) suggests that readers may actually need to proceed through all stages with every single word in order to assure efficient processing.

Usually, the development of fluency is associated with huge amounts of experience with print. Furthermore, the different accounts agree on that the instant recognition of words is fundamentally phonologically underpinned (e.g. Perfetti & Liu, 2005). These assumptions lay the foundation of the self-teaching hypothesis (Share, 1995), in which it is proposed that words can only be stored as orthographic representations if they can be decoded correctly. According to this hypothesis, phonological recoding of new words comprises a self-teaching mechanism, which provides an opportunity to acquire word-specific orthographic information and thereby facilitates fast word recognition. Evidence in support of the self-teaching hypothesis comes from various studies (Share, 1999, 2004; Cunningham, 2006). The self-teaching mechanism also appears to be active in silent reading (De Jong & Share, 2007). The ability to use contextual information is thought to be important, because in cases of partial decoding it can provide clues on how words are pronounced (Share, 1995). In a recent study, Landi et al. (2006) confirmed this assumption, but interestingly, they also found that retention was superior for words learned in isolation. Moreover, this benefit from learning in isolation was larger for less skilled readers. Landi and colleagues explained their findings by stating that semantic context allows the readers' attention to be drawn away from word decoding. Since less skilled readers have a greater need to focus on letter-sound processing due to their poorer decoding skills, less attention to the word form will have more serious consequences for them.

The idea that phonological decoding provides the fundamental basis for the subsequent development towards a more fluent reading proficiency, or as Share describes it, that phonological decoding is the sine qua non of reading acquisition, is supported by more general accounts of skill acquisition. According to Siegler's (2005) model of learning and development, learning is the result of a metacognitive and an associative mechanism, which interact to produce a single acquisition. Research on this model indicated that when children are novices in a domain, the explicit metacognitive learning mechanism plays an important role by explicitly directing each step in a strategy, thereby feeding the associative system. With growing experience, the role of the metacognitive system diminishes while the associative mechanism develops a fast, automatized analogue of the metacognitive version of the skill (Crowley, Shrager, & Siegler, 1997). Correspondingly, it has been revealed that full automaticity of grapheme-phoneme associations, in the sense that they become instrumental in fluent reading, takes much longer than the acquisition of passive knowledge of them (Blomert, 2005; Sprenger-Charolles et al., 2006).

Although the efficiency of decoding is normally considered the major distinctive component of reading fluency, Wood, Flowers, and Grigorenko (2001) stress the additional importance of anticipatory processing. The idea is that preliminarily processing of the words yet to come, facilitates the subsequent response to them. Besides this "proactive" facilitation, there is also "retroactive" facilitation, in which the identification of a word is influenced by the familiarity of a succeeding word or words. In general, the function of anticipatory processing in fluency emphasizes the importance of goal-directedness in learning to read (Wood et al., 2001; see also Usacheva, Lazareva, Vostrikova, & Shcherbakova, 2007). The role of anticipatory processing has already been demonstrated within the Rapid Automatized Naming (RAN) paradigm, in which processing of laterally displayed series of individual items (such as colors or numbers) seems to be faster than that of separately presented stimuli (Wolf, 1991). In the end, as argued by Wood et al. (2001), just as dancing becomes fluent by the integrative processing and execution of a sequence of postures, skilled, fluent reading is characterized by integrative, and therefore anticipatory, processing more than with item-by-item recognition and response.

Current accounts on enhancing reading fluency

As noted earlier, one consistent finding in dyslexia research is that, despite their success in ameliorating accuracy in reading and spelling, traditional interventions are insufficiently able to normalize reading fluency. However, a number of different instructional approaches have been specifically developed to improve fluency. Some of these approaches have been designed for the classroom, while others are intended for individual remediation. Unfortunately, the circumstances in which these approaches are executed are far less structured than those within traditional treatment, which makes the existing data regarding their effectiveness less adequate for scientific analyses. Moreover, the heterogeneity of the target group also hinders reliable inferences. Nevertheless, some valuable review studies have been published (Chard, Vaughn, & Tyler, 2002; Kuhn & Stahl, 2003). In the overview by Kuhn and Stahl, detailed descriptions of the various methods can be found. It seems that fluency instruction is generally effective (Kuhn & Stahl 2003), although no evidence is available that fluency-oriented approaches can produce normalization of fluency in individuals with dyslexia (Torgesen, 2005).

Furthermore, it is unclear whether the effectiveness of these approaches is the result of specific instructional characteristics or just the consequence of augmented reading experience (Kuhn & Stahl, 2003).

Many authors stressed the essential role of extensive reading experience in the development of reading fluency (Kuhn & Stahl, 2003; Nathan & Stanovich, 1991; Torgesen 2005; Torgesen & Hudson, 2006). A major consequence of limited reading practice is that the amount of words in the instant recognition repertoire remains small (Ehri, 2002). Notably, in a frequently cited study by Anderson, Wilson, and Fielding (1988), it was investigated how much time 5th graders spend on reading outside school. Ample differences were found between good readers and poor readers in the amount of reading. Their data suggested that an entire year's worth of out-of-school reading for the child at the 10th percentile of reading ability equals just 2 days' reading for the child at the 90th percentile (Torgesen, 2005). In a series of studies, Cunningham and Stanovich expanded on the topic of print exposure and its relation to cognition (e.g. Cunningham & Stanovich, 1998, 2003; Stanovich & Cunningham, 2004). They found that individual differences in word recognition ability are, at least in part, determined by print exposure differences (Cunningham & Stanovich, 1993).

Accordingly, most fluency-oriented instructional programs include extensive amounts of reading practice. We will focus here on repeated reading, the most familiar and most researched approach to fluency training. This technique consists of repeatedly reading passages of text or isolated words, until a certain rate is reached.

Repeated reading of isolated words was traditionally put into practice using index cards containing the intended words. These so called flashcards were presented within a specific time period (usually less than a second). Nowadays, this flashcard paradigm is commonly used within practice, though in a computerized fashion, i.e., words are shortly presented on a computer screen. Evaluation studies indicate that flashcard training can enhance the reading rate of poor readers (Berends, 2005; Berends & Reitma, 2006; Martin-Chang & Levy, 2005). Children learn to read the presented words faster and more accurate after a few sessions and there seems to be no decline at all in treatment gains after the treatment has stopped (Berends, 2005). However, there is no evidence that reading rate can be normalized in the poorest readers with this kind of training (Berends, 2005; Thaler, Ebner, Wimmer, & Landerl, 2004). Furthermore, studies failed to reveal substantial transfer of effects (Berends & Reitsma, 2006; Hintikka, Landerl, Lyytinen, & Aro, 2008). Of course, it can still be useful to practice with flash cards, even without transfer effects. After all a reader can elaborate its instant recognition repertoire by this means and it seems that only few encounters with a word are necessary to store its orthographic form in long term memory (Reitsma, 1983). However, in the case of dyslexia it is consistently reported that much more repetition is needed (Hintikka et al., 2008; Reitsma, 1983; Thaler et al., 2004). In the absence of transfer effects, flashcard training is therefore less suited for individuals with dyslexia. Recent studies suggest that emphasizing sub-lexical units instead of words within the flashcards paradigm might be a promising way of enhancing generalization of effects (Hintikka et al., 2008; Martens & de Jong, 2006).

The understanding of reading fluency has grown significantly with the rise of cognitive neuroscience. In the next section, we will discuss how the behavioral aspects of fluent reading are anchored in the brain, what is different in the dyslexic brain, and what connectionist models tell us about how reading fluency originates. Furthermore, we will explore other areas of expert learning in the light of reading fluency.

A cognitive neuroscientific perspective

The rise of neuroscience, with its rapid development of functional neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), and its sophisticated modeling of neural networks, has brought a wave of new insights into learning and development. Therefore, it is not surprising that there is a considerable amount of optimism about the valuable contribution neuroscience can make to education (Battro, Fischer, & Léna, 2008; Szűcs & Goswami, 2007; Varma, McCandliss, & Schwartz, 2008). Uncovering how fluency develops in the normal brain and how it is disrupted in the dyslexic brain, can help us find effective ways to enhance it.

Fluent adult readers are able to identify written words in a split second. The functional organization within their brain is globally divided into a posterior dorsal system and a posterior ventral system, which are respectively associated with phonological and orthographic processing (Pugh et al., 2001; Schlaggar & McCandliss, 2007). The dorsal system, which comprises mainly the perisylvian region including the supramarginal gyrus, angular gyrus, and superior temporal cortex, is believed to be specifically important for accuracy within the reading process, where the ventral system, which includes lateral extrastriate areas and a left occipito-temporal area, is assumed to be specifically related to fluency (Lyytinen et al., 2005; Pugh et al., 2001).

Converging findings indicate that both the dorsal component and the ventral component are impaired in dyslexia, which is functionally manifested by decreased activity. Evidence comes from functional neuroimaging studies (Brunswick et al., 1999; Paulescu et al., 2001; Shaywitz et al., 1998; Temple, 2002) as well as from anatomical accounts (Beaulieu et al., 2005; Gaillard et al., 2006; Galaburda, 1992; Klingberg et al., 2000; Niogi & McCandliss, 2006). To the contrary, activation in inferior frontal and right hemisphere posterior regions is heightened in reading-disabled individuals, relative to nonimpaired readers (Brunswick et al., 1999; Shaywitz et al., 2002). This atypical frontal and right hemispheric activation is commonly attributed to compensatory strategies (Pugh et al., 2001; Shaywitz et al., 2002). The neurobiological dysfunction in left hemisphere posterior reading circuits is already present in reading-disabled young children and is not the result of a lifetime of poor reading (Shaywitz et al., 2002; Temple et al., 2001).

As reading fluency is the focus of this discourse we will elaborate on the associated posterior ventral system. Converging evidence indicates that a functional specialization within this system is responsible for the kind of perceptual expertise that is seen in fluent reading (Cohen et al., 2000; McCandliss et al., 2003; Cohen et al., 2002). This functional specialization is currently designated as the visual word form area (VWFA), although its specificity has been under continuing debate (Cohen et al., 2004; Price & Devlin, 2003). The VWFA is characterized by fast and parallel identification of letter strings, irrespective of case, font, size, and retinal position (McCandliss et al., 2003) and can be seen as the biological source behind the earlier mentioned ‘instant recognition repertoire’. The causal role of the VWFA in reading is supported by lesion studies (Gaillard et al., 2006; Philipose et al., 2007). The VWFA is sensitive to learned letter stimuli, but not to other control shapes nor spoken words (McCandliss et al., 2003). VWFA responses are even measurable when a subject perceives a word unconsciously (Dehaene et al., 2001). The VWFA is among the most consistently activated regions in quantitative meta-analytic studies of adult reading (Schlaggar & McCandliss, 2007) and its exact location within the left mid-fusiform gyrus seems to be very consistent across individuals (Jobard et al., 2003) and across cultures and writing systems (Bolger et al., 2005).

Most research on the VWFA uses skilled adult readers as subjects, which represent the end-state of reading development. However, in order to understand the emergence of fluent reading on a neural level, it is particularly important to focus on the changes the brain undergoes in the process of acquiring the skill. Developmental studies suggest that VWFA responses are tightly correlated with reading skill (Shaywitz et al., 2002) and that during the ages when reading skill is acquired, a transition takes place from bilateral occipitotemporal involvement to a predominance of left-lateralized occipitotemporal involvement (Turkeltaub et al., 2003). The perceptual expertise which is associated with the VWFA seems to develop gradually with reading experience and is still not at adult levels even after five years of reading practice (Aghababian & Nazir, 2000). Sandak et al. (2004) found that increased activity in a left ventral occipitotemporal region correlates more with reading skill than with age, which suggests that experience is involved in the functional development of this region. In a longitudinal study Shaywitz and her colleagues (Shaywitz et al., 2004) were able to link improved reading skill in reading disabled children after intervention with increased activity of the VWFA. This result also supports the assumed role of experience in the development of the ventral region and emphasizes the importance of educational activities.

Further insight in the developmental course of the VWFA comes from event-related potential (ERP) studies. ERP studies in skilled readers have shown that visually viewing a word leads to peaks between 150 and 200 ms, which are characterized by posterior negativity. Specifically the left-lateralized N170 (or N1) response has been linked to activity of the VWFA (Brem et al., 2006). The reading-related N170 response is also manifest in tasks that do not require the words to be read, and consequently appears to be automatic (Maurer et al., 2005). In reading disabled adults, specific activity for visual words seems to be absent within the 150 and 200 ms timeframe (Helenius et al., 1999).

Evidence for an experience-based nature of this N170 response comes from different studies. Maurer et al. (2005) found that, although many of the participating 6-year-old kindergarten children were familiar with letters, their N170 responses were delayed, not solely sensitive for visual words, and not lateralized to the left hemisphere. The adults, participating in the same study, by contrast showed the expected left-lateralized activation within 200 ms when presented with visual words. In consecutive studies Maurer and colleagues (Maurer et al., 2006; Maurer et al., 2007) followed the children from the previous study longitudinally and found that a N170-like response for visual words emerged within two years of formal reading instruction and that the coarse tuning appeared stronger for the more skilled readers, which supports the notion of an experience-based nature. The results also demonstrated that visual tuning for print, as well as the behavioral measures of reading skill, developed more slowly in children who later were diagnosed with dyslexia. Comparing 2nd graders and adolescents with adults within the same paradigm revealed further changes in the N170 response for visual words compared to other visual stimuli, presumably reflecting augmented reading experience (Maurer et al., 2006; Brem et al., 2006). Another ERP study with four, seven, and ten-year-old children, showed that only at age ten a small but delayed N200 response with sensitivity to words over consonant strings, occurred (McCandliss, Posner, & Givon, 1997).

Until now, the global activation of the VWFA has been the major target of investigation, however recently the internal organization of this region has received significant attention as well (Bolger, 2007; Dehaene et al., 2005; Dehaene, 2008; Vinckier et al., 2007). Vinckier et al. (2007) found evidence for a posterior to anterior hierarchical organization of neurons, responding to increasingly larger and complex components of words. This means that with more anterior or left-lateralized activity, there is an increasing preference for stimuli resembling real words. Vinckier and colleagues conclude that this hierarchical organization must result from a tuning process during reading acquisition. Interestingly, this is in line with the stage-like models (e.g. Chall, 1996; Ehri, 2002) of reading development within the cognitive domain. From this point of view, the VWFA can be seen as the neural counterpart of this tuning process, whereas the stage-like development of reading represents the behavioral equivalent of the same tuning process. When this tuning process is efficient, the developing reader becomes sensitive to increasingly larger components within words, resulting in instant word recognition, facilitating fluent reading.

Unifying the various neurological insights regarding normal and disrupted reading development, members from the Haskins laboratories (Pugh et al., 2001) proposed a tentative model, which subsequently received support from other authors (McCandliss & Nobel., 2003; Schlaggar & McCandliss, 2007). In their view, the development of the posterior dorsal reading system acts as a bootstrapping mechanism for the subsequent development of the posterior ventral system. Whereas the dorsal region is involved in learning to decode print, the ventral region develops with reading experience into a system that identifies words in an automatic manner. Consequently, deficient dorsal function will fail to support adequate ventral development. The shift to inferior frontal activity reflects a compensatory strategy in which articulatory support is pursued in order to cope with phonological processing difficulties. The second shift, from left to right hemispheric ventral activity, is likely to be associated with more general visual compensatory strategies.

Correspondingly, within reading acquisition the reader initially depends on the dorsal circuit to learn to decode, which, with more efficient attention to regularities of grapheme-phoneme mapping, feeds the gradual specialization of the ventral system (McCandliss & Nobel, 2003; Pugh et al., 2001). This model fits well with the cognitive accounts of reading acquisition proposed by Ehri (2002) and Chall (1996) and with Siegler’s model of learning and development (Siegler, 2005). As we will show in the next paragraph, similar developmental progression is seen within connectionist models.

Connectionist models of reading acquisition

Connectionist models are designed to approximate the core properties of neural computation and offer us new ways of studying reading acquisition. Assumptions about cognitive processes can be tested by simulating them in artificial networks. In the last two decades, various models have provided insights about many aspects of normal reading and disrupted reading (Lupker, 2005; Plaut, 2005; Seidenberg, 2005). In the present discourse, we will focus on models that 'learn' to relate print to speech and meaning. One of the most prominent of these models is the triangle framework, which was introduced in the late eighties by Seidenberg and McClelland (1989) and elaborated in subsequent years (Seidenberg, 2005). The triangle framework is based on the assumption that word recognition involves orthographic, phonological, and semantic representations. First, the model needs to learn connections between phonology and semantics. Once the model reaches a certain level of proficiency in these connections, orthography is introduced additionally. By this, the model mirrors the real situation in which a child already has well-developed knowledge about sounds and meanings of words when reading instruction starts. Simulations with this model show two occurring pathways from print to meaning: a direct pathway from orthography to semantics and an indirect pathway from orthography to phonology and from phonology to semantics. Interestingly, early in the model's training semantic activation largely depends on the phonology-mediated pathway. Over time, however, the direct pathway becomes more dominant, particularly for high-frequency words. Nevertheless, when a high level of proficiency is reached, the phonology mediated pathway still contributes considerably. Clearly, this model shows high resemblance with cognitive accounts on reading acquisition. Early on, decoding is the central aim of attention, but with experience, word recognition becomes an automatized process.

In another connectionist model, Harm and colleagues (Harm & Seidenberg, 1999; Harm, McCandliss, & Seidenberg, 2003) investigated the consequences of manipulating neural properties of the phonological system on reading performance. Interestingly, their model began to exhibit symptoms of dyslexia after simulating neural damage to the phonological system in advance. As summarized by Sprenger-Charolles, Colé, and Serniclaes (2006), experimental studies revealed some interesting findings related to these network models. It was shown that in visual word recognition the activation of orthographic codes precedes the activation of phonological codes in time, which on their turn precede the activation of semantic codes (Ferrand & Grainger, 1993; Perea & Gotor, 1997). Moreover, results revealed that phonological codes are activated earlier and more automatically in skilled readers than in less skilled readers (Booth, Perfetti, & MacWhinney, 1999), and individuals with dyslexia show a deviant activation of the phonological codes of written words (Booth, Perfetti, MacWhinney, & Hunt, 2000). In connectionist network terms, these results suggest a dysfunction at the phonological level and/or a disrupted development of connections between orthography and phonology in dyslexic readers.

Taken together, it can be concluded that the characteristics of these connectionist network models of reading are in accordance with the aforementioned neurofunctional findings on fluent and dyslexic reading. Another field of research which enjoys huge amounts of attention from cognitive neuroscience and which can contribute to the current discourse is that of expert learning.

Expert learning

Generally, there is only a small number of experts within a domain, in the case of reading the opposite seems true, i.e., within literate society just a minority fails in becoming an expert reader. Consequently, high reading proficiency is easily taken for granted and the ostensible naturalness of skilled reading can restrain us from thinking about it as a form of expertise. Considering reading acquisition as a form of expert learning gives us the opportunity to explore other areas of expert performance and to derive new insights from them, which can be useful for reading instruction.

In recent years, cognitive neuroscience played an important role in uncovering the underlying neural mechanisms in chess expertise. Since De Groot's (1949) seminal doctoral dissertation on chess expertise it is known that, contrary to what is commonly thought, skilled players do not think further ahead than less skilled practitioners. What makes them different though, is their strikingly superior memory for briefly presented chess positions. However, subsequent research by Chase and Simon (1973a, 1973b) revealed that this superior perceptual memory only holds for legal chess positions, i.e., when pieces are randomly arranged on the board skilled players perform only slightly better than novices. Interestingly, in a recent fMRI study it was revealed that chess experts recruit neural mechanisms in the posterior ventral circuit, just as skilled readers do (Righi & Tarr, 2004). So, it is plausible that a specialized neural mechanism, analogues to the VWFA, is responsible for fast identification of meaningful configurations on the chessboard. This clarifies the preference for legal positions, and fits with existing cognitive accounts on the nature of superior perceptual abilities in chess, in which it is assumed that chess experts perceive positions in meaningful chunks (Chase and Simon, 1973a) and templates (Gobet & Simon, 1996). Moreover, as witnessed by Capablanca's introspective description of his abilities, it confirms that in chess, just as in reading, the expert experiences its high proficiency as a "reflex".

Interestingly, as shown by fMRI and ERP studies, the role of the posterior ventral system in visual expertise is not restricted to reading and chess, but also seems to play part in the identification of faces (McKone, Kanwisher, & Duchaine, 2007) birds and dogs (Tanaka & Curran, 2001), cars (Gauthier, Curran, Curby, & Collins, 2003), fingerprints (Busey & Vanderkolk, 2005), and even 'greebles', which are newly created 3D figures for experimental use (Rossion, Gauthier, Goffaux, Tarr, & Crommelinck, 2002). Thus, it seems that with appropriate experience a pre-existing natural brain system can be efficiently reused for various cultural purposes, including reading and chess playing (Dehaene & Cohen, 2007; Dehaene, 2008). However, what appropriate experience is necessary to obtain high proficiency? In the case of expert recognition of faces, birds, dogs, cars, fingerprints, and greebles, it seems that repeated encounters with members within these classes are sufficient to induce neural specialization. In the case of chess, more is needed. Since, chess proficiency depends on a combination of slower heuristics and fast pattern recognition, mere exposure is not sufficient. It seems that, just as in reading, there must be a high level of familiarity with the game and a thorough understanding of the dynamics, before subsequent repetition and practice will ultimately lead to fast recognition of game situations (Gobet & Jansen, 2006). Yet, many years of subsequent practice are necessary to obtain mastery (Charness et al., 2005; Gobet & Campitelli, 2007). In a classical study, Simon and Chase (1973) estimated that it takes about ten years of intensive practice to become an expert in chess. Nevertheless, there seems to be substantial variability in the number of practice hours among skilled players (Gobet & Campitelli, 2007). Thus, domain-specific practice is necessary, but not sufficient, to acquire an expert-level. As in reading, it is likely that the success of practice depends on the preceding level of understanding and on the way, practice is substantiated. It is interesting in this light that it has been shown recently that there is a speeding-up in the time to reach high levels of expertise (Gobet & Campitelli, 2007), i.e., the amount of young chess grandmasters has augmented significantly during the last decade. Changes in training methods, particularly the emergence of computerized databases, might be the cause of this phenomenon (Gobet & Campitelli, 2007). Computerized databases facilitate repetitive exposure to relevant positional configurations and, by that, provide opportunities to feed the instant recognition repertoire of frequent chess situations.

A recent review by Gobet and Jansen (2006), in which various training techniques are compared, sheds further light on the dynamics of successful practice in chess. Gobet and Jansen infer several educational principles from their findings which must result in the emergence of chunks and templates, viz, the elements to be learned must be clearly identified, complexity must increase gradually, the focus must be limited constantly to a small number of positions at a time, vast repetition is vital, resources must be employed efficiently, specific attention must be given to typical situations, and motivation must be maintained for long periods. In addition, Ferrari, Didierjean, and Marmèche (2006) highlighted the anticipatory component of expert perception in chess.

In conclusion, there are similarities between the development of skilled reading and the development of expert chess playing, both on a neurological level and on a behavioral level. Therefore, it is no surprise that within both areas of research, conclusions about the dynamics that lead to high proficiency, coincide.

New directions for treatment

The aim of the current chapter is to contribute to the quest for educational principles that could enhance reading fluency in the reading disabled. After having focused on the dynamics of reading fluency from a behavioral perspective as well as from a neuroscientific perspective, what conclusions can we draw concerning fluency-oriented instructional practices? In the current section we will try to answer this question by integrating various insights from the preceding sections. In addition, some promising new directions for dyslexia treatment will be proposed. We will end this section by presenting a software program, called LexyLink, which we consider as an example of an innovative fluency-oriented approach.

There is general agreement that in order to become a skilled reader the slow and laborious reading that marks the initial phase, must be substituted somewhere in time, by instant recognition of words (Ehri, 2002; Torgesen & Hudson, 2006; Share, 1995). In alphabetical scripts, such as English, Dutch, Korean, and Russian, the mastery of grapheme-phoneme correspondences is a key aspect in reading acquisition (Atteveldt, Formisano, Goebel, & Blomert, 2004; Sprenger-Charolles et al., 2006). Familiarity at this fundamental level could pave the way for subsequent learning of phonemic and orthographic regularities (Chall, 1996; Share, 2004). However, it is noted that full automaticity of grapheme-phoneme associations in the sense that they become instrumental in fluent reading takes much longer than the acquisition of passive knowledge of them (Blomert, 2005; Froyen, Bonte, van Atteveldt & Blomert, 2009; Sprenger-Charolles et al., 2006). Knowing the associations between letters and speech sounds appears to be only the starting point of the development toward automatic letter-speech sound integration (Froyen et al., 2009). In our opinion, it is therefore essential to train grapheme-phoneme correspondences vastly in individuals with dyslexia. Traditional approaches are less appropriate for this purpose, because they lack the needed intentionality and do not account for the time demands associated with audiovisual letter integration. Several neurofunctional studies demonstrated that the integration of speech and visual stimuli takes place within a very brief time window (e.g., Froyen et al., 2009; Raij et al., 2000). Consequently, we advocate extensive and intentional repetitive training of grapheme-phoneme correspondences, considering the required time demands. The aim of this training should be a neural tuning process, which takes the mastery of these correspondences to a higher level.

Another step in the pursuit of an instant recognition repertoire in reading seems to be the set-up of a strong foundation of explicit knowledge of phonemic and orthographic regularities, as well as the unfolding of powerful decoding skills. High levels of familiarity within these domains in combination with increasing experience are considered to act as a bootstrapping mechanism for the subsequent tuning towards an instant recognition repertoire. As we saw in the preceding sections, this view is strongly supported by cognitive (Chall, 1996; Ehri, 2002; Share, 1995; Siegler, 1995; Sprenger-Charolles et al., 2006), neurobiological (McCandliss & Nobel., 2003; Pugh et al., 2001; Schlaggar & McCandliss, 2007), and connectionist (Harm, McCandliss, & Seidenberg, 2003; Harm & Seidenberg, 1999;

Seidenberg, 2005; Seidenberg & McClelland, 1989) models of reading acquisition, and shows striking parallels with other areas of expert proficiency. The notion of bootstrapping is further supported by the finding that the enhanced accuracy leads to further development of reading rate after specialized phonology based treatment (Tijms, 2007).

The problem in the case of dyslexia is that individuals with dyslexia will not capitalize on experience as long as their decoding skills fall short. Consequently, at the time they start to take advantage of reading experience they have to make up for the huge deficits in reading practice they have accumulated over time. An enormous amount of experience is needed to close this gap, which is additionally hindered by the fact that individuals with dyslexia have a limited inclination to engage in reading (Torgesen, 2005). Experimental studies confirm that individuals with dyslexia need much more exposure and repetition in order to learn words by sight (Hintikka et al., 2008; Reitsma, 1983; Thaler et al., 2004).

Ehri (2002) argues that some “mnemonically powerful” system must be responsible for learning words by sight. It is plausible that on a neurobiological level this system is embodied by the putative VWFA. The responsivity of this area grows with increased experience (Vinckier et al., 2007), which seems to be a relatively slow process. Accordingly, there is general agreement on that reading fluency only emerges after extensive reading experience (Kuhn & Stahl, 2003; Nathan & Stanovich, 1991; Torgesen 2005; Torgesen & Hudson, 2006). This is also in line with findings from other areas of expert learning where different authors concluded that it takes about ten years to become an expert within a given domain (Ericsson, Krampe, & Tesch-Römer, 1993; Simon & Chase, 1973).

So how should extensive practice be arranged in order to be successful in enhancing the reading fluency of individuals with dyslexia? Again, we propose massive and intentional repetitive training of correspondences between sounds and their graphic representations in scripts, including whole words, but rather than to close the gap after traditional intervention has been completed, we argue that this repetitive exposure should take place simultaneously. Thus, instead of letting experience do its job after general accuracy is restored by explicit intervention, we propose an organization in which every explicit instruction will be elaborated by additional intentional boosting. By this means one can start building on the instant recognition repertoire right away, because every single achievement on an explicit level will be exploited immediately to bring about automatization. This idea is reconcilable with Share’s idea of item based development, in which for some words the reader must rely heavily on effortful decoding, while other words are already processed automatically (Share, 1995). Wood et al. (2001) also plead for fluency training as a background for phonology based training rather than as an “add-on” after phonology based training has been accomplished.

Within this proposal it is important that the used material, as well as the presentation order, is selected carefully. As stated before, the initial focus must lie on isolated phonemes. Then, the attention can slowly be shifted to increasingly larger word fragments and ultimately whole words, mirroring the natural development of the VWFA and its hierarchical organization. The earlier mentioned findings of Hintikka and colleagues (2008), in which they found that flashcards training was more effective when sub-lexical units were used as target instead of words, are interesting in this light. When using whole words finally, we argue that it is preferable to use real words instead of pseudowords, to nourish the goal-directedness in learning, as advocated by both Wood and colleagues (2001) and Usacheva and colleagues (2007). For the same reason it is good to emphasize the purpose of learning frequently and to invite the pupil to think ahead. Of course, much of this can be done during the phase of explicit instruction. On the other hand postponing a semantic context could be beneficial particularly in the initial phase, because, as stated earlier, it allows the readers’ attention to be drawn away from word decoding (Landi et al., 2006).

On a neurobiological level building an instant recognition repertoire can be seen as an increasing tuning of neurons for script based stimuli, as a consequence of repeated exposure (Vinckier et al., 2007; Wood, Flowers, and Grigorenko, 2001). Mahncke, Bronstone, and Merzenich, (2006) describe this as the strengthening of the signal-to-noise ratio of relevant cortical activity. Naturally this kind of learning proceeds on the basis of distributional information, without directed attempts to learn, and without requiring teaching signals (Munakata & Pfaffly, 2004). Consequently, we propose that fluency training should comprise a more implicit associative form of learning in which this neuronal tuning process is facilitated.

Another important issue is the scheduling of the training sessions. Capitalizing on the malleability of the brain requires a substantial training schedule in which the desired skill must be practiced over hundreds of times (Mahncke, Bronstone, & Merzenich, 2006). Furthermore, continuity must be preserved by limiting inter-session interval time, i.e., Thaler and colleagues (2004) found that within fluency training, the weekend break already led to a slight decrease in reading speed.

Summarizing, we propose a training paradigm aimed at enhancing reading fluency, in which associative learning by massive exposure to phonemes, both isolated and as a part of word fragments and whole words, is combined with traditional explicit intervention methods. In the following paragraph we will argue that edugames offer a promising framework for realizing our suggested educational goals.

The unique possibilities of edugames

Edugames are computer programs, which are designed for teaching certain skills. They provide unique possibilities to educators because learning dynamics can be controlled automatically and motivation can be brought off for prolonged periods of time. Moreover, computer aided instruction is low-cost in modern society and can be easily applied in different settings, such as school or home.

On a cognitive level edugames are advantageous because the learning dynamics can easily adapted to the pupils needs. The complexity of the educational contents for example, can be maintained within the “zone of proximal development”, providing an optimal level of cognitive stimulation and minimizing failure (Wilson et al., 2006). If the game is designed in such a way that educational aspirations coincide with game objectives, a form of implicit learning arises which is highly effective.

For our specific purposes the edugame paradigm is particularly suitable because it offers the possibility to establish massiveness of exposure, within a highly motivational environment. Notably, when it is aimed to expose subjects many hundreds of times to more or less the same stimuli, they must be willing to play the game, preferably without asking them. However, if properly designed, computer games are highly motivational because they meet the universal criteria of enjoyableness (Johnson & Wiles, 2003). In an extensive study Csikszentmihalyi (1990) explored the characteristics of enjoyableness and concluded that we are inclined to engage in an activity if it can be completed, demands concentration, has clear goals, provides immediate feedback, leads to a sense of control, demands a deep involvement that removes awareness of everyday life frustrations, leads to a lack of concern for self, and alters the sense of time. Mahncke, Bronstone, and Merzenich, (2006) take the concept of motivation somewhat further and argue that from a neurobiological point of view arousal, attention, reward, and novelty must be capitalized, because the associated release of specific neurotransmitters can strengthen learning and memory. Again, edugames can be particularly appropriate to meet these goals.

Another advantage of edugames is that it is relatively easy to integrate specific time demands. There are various possibilities, such as timekeepers, time bonuses, and time limits, to encourage subjects to respond quickly. This aspect is also significant within our proposal, because time demands are needed to ensure high exposure frequency within a short period, and to respect the time course that is associated with audiovisual letter integration.

Edugames have been applied successfully in several domains, among which: dyscalculia (Wilson et al., 2006), specific language impairment (Merzenich et al., 1996), and aging (Mahncke et al., 2006). The open-source software “The Number Race”, designed for remediation of dyscalculia, is an interesting example of an adaptive edugame in which repeated exposure is used for strengthening the links between representations of number (Wilson et al., 2006). The authors used a multidimensional learning algorithm, containing the dimensions numerical distance, speed, and conceptual complexity, to constantly adapt the difficulty of the program to the child’s performance level. The speed dimension was implemented to increase automaticity.

A game that is specifically designed for dyslexia prevention and which is based on repetitive exposure to grapheme-phoneme associations is the “Graphogame” (Richardson, 2008). The game’s aim at neural tuning fits with our educational propositions. However, as opposed to our suggestions, the “Graphogame” does not combine this implicit method with traditional explicit approaches. The effectiveness of this game is currently under investigation in four European countries.

We will end this section by presenting LexyLink, an edugame we developed with the aim of substantiating our educational propositions.

An innovative approach: LexyLink

The theoretical issues, discussed earlier in this chapter, inspired us to set up a project on the development and implementation of more elaborate associative learning mechanisms in an existing treatment program for dyslexia, called LEXY (see Tijms, 2005 for a detailed description of the program). This traditional computer based treatment presents pupils with dyslexia with a learning system clarifying the basic linguistic elements and operations that are essential for the graphic representation of spoken language and guides the recognition and use of the phonological and morphological structure of Dutch words.

It was shown that this treatment results in clinically relevant improvements in reading and spelling, i.e., for text reading accuracy and spelling, most of the participants attained a level of proficiency equal to, or above, the normative average for these skills (Tijms, 2005). In concordance with general findings, one notable result is that reading rate is less susceptible to intervention than reading accuracy. Therefore, by implementing a complementary edugame in the treatment program, we aim to accelerate reading rate as a fundamental aspect of reading fluency.

In this project pupils with dyslexia attending the LEXY program will be presented with a complementary software program, called LexyLink, which has an implicit foundation. This software consists of a challenging computer game in which the pupil has to match sounds to their corresponding graphic representations. Correct associations lead to success in the game, while incorrect associations jeopardize a positive outcome. Fast playing is reinforced by progressive time restrictions and by giving time bonuses.

The design of the software was based on the aforementioned educational principles. Through this game pupils will be massively exposed to associations between sounds and their graphic representations. The specific contents of LexyLink will be matched consistently with the ingredients from the preceding LEXY session. Consequently, any explicit lesson is followed by an extensive associative elaboration of its contents. By enhancing the pupils' explicit knowledge and decoding skills in advance, full advantage can be taken of the intentional massive exposure. An illustration of a Dutch word that could be the target of explicit instruction is "sla" (lettuce), which is pronounced as /slaa/. Since the long vowel ends the syllable, it is written with one graph. By contrast, in the word “slaap” (sleep), which is pronounced as /slaap/, the long vowel /aa/ has its standard Dutch representation comprising two graphs. In LexyLink this specific rule can be easily practiced in a more associative implicit fashion. For example, by asking the subject to relate the stimulus phoneme /aa/ to balloons containing the response orthographical representations (“sla” or “slaap”), while avoiding balloons containing distractor words which lack the phoneme in question, but share some graphic similarities, such as the word “slap” (weak). This word is pronounced as /slap/ and thus contains a short vowel /a/ instead of a long one. So, the treatment is organized in a way that mimics the putative bootstrapping mechanism, discussed earlier, and that facilitates neural tuning.

The fact that LexyLink aims at exposing children with dyslexia massively to the associations between sounds and their graphic representations, places high demands on the attractiveness of the game, because obviously massive exposure can only occur if the child is willing to play frequently. Therefore much attention is given to the enjoyableness of the game. Importantly, the basic associative principle of the game is enjoyable by itself because it meets Csikszentmihalyi’s (1990) criteria. Nevertheless, we added some external motivational components to ensure maximum engagement, such as time bonuses, rewards for accomplishing levels, and a high score list. However, we avoided decorative motivational elements, like additional images and funny noises, because these make an unnecessary appeal on cognitive resources.

Summarizing, we aim to accelerate the growth of reading fluency by boosting the development of instrumental grapheme-phoneme associations within a computer game environment.

Conclusion

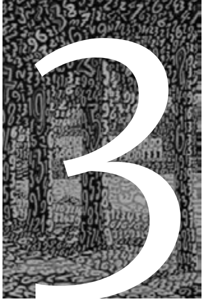
In this chapter we engaged in a theoretical quest for ways to foster reading fluency in children with dyslexia. We started by giving an overview of research regarding fluent reading and disrupted reading, with special attention for state-of-the-art findings from cognitive neuroscience.

Amalgamating insights from cognitive, neurobiological, and connectionist models, as well as from the paradigm of expert learning, we drew several conclusions regarding fluency-oriented instructional practices and proposed some new directions for dyslexia treatment. Our proposals can be summarized in the following way:

1) Nourish familiarity of grapheme-phoneme correspondences: The mastery of grapheme-phoneme correspondences is a key aspect in reading acquisition. Familiarity at this fundamental level could pave the way for subsequent learning of phonemic and orthographic regularities. We advocate extensive and intentional repetitive training of grapheme-phoneme correspondences. This training must continue until these correspondences are really well anchored in the brain.
2) Start building on the instant recognition repertoire right away: Individuals with dyslexia will not capitalize on experience as long as their decoding skills fall short. We propose massive and intentional repetitive training of correspondences between sounds and their graphic representations in scripts, including whole words, but rather than to close the gap after traditional intervention has been completed, we argue that this repetitive exposure should take place simultaneously, i.e., every explicit instruction should be elaborated by additional boosting.
3) Focus on increasingly larger word fragments: It is important that the used material, as well as the presentation order, is selected carefully. The initial focus must lie on isolated phonemes. Then, the focus should slowly be shifted to increasingly larger word fragments and ultimately whole words, mirroring the hierarchical organization of the VWFA.
4) Invite for anticipatory processing: We argue that it is preferable to use real words instead of pseudowords, to account for goal-directedness in learning. It is important to emphasize the purpose of learning frequently and to invite the pupil to think ahead. In the end fluent reading is characterized by integrative and anticipatory processing.
5) Control the time frame: Capitalizing on the malleability of the brain requires a substantial training schedule in which the desired skill must be practiced over

hundreds of times. Furthermore, continuity must be preserved by limiting inter-session interval. The integration of speech and visual stimuli takes place within a very brief time window. Therefore, time demands should be taken in consideration.

6) Capitalize on educational software: Edugames provide unique possibilities to educators because learning dynamics can be controlled automatically and motivation can be brought off for prolonged periods of time. Moreover, within edugames our proposed educational principles can be effectively substantiated. From a neurobiological point of view edugames provide a way of capitalizing on the release of specific neurotransmitters which are associated with arousal, attention, reward, and novelty, and which strengthen learning.



3
CHAPTER

A lab-controlled simulation of a letter-speech sound binding deficit in dyslexia

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Abstract

Dyslexic and typical readers engaged in a short training aimed at learning eight basic letter–speech sound correspondences within an artificial orthography. We examined whether a letter–speech sound binding deficit is behaviorally detectable within the initial steps of learning a novel script. Both letter knowledge and word reading ability within the artificial script were assessed. An additional goal was to investigate the influence of instructional approach on the initial learning of letter–speech sound correspondences. We assigned children from both groups to one of three different training conditions: (a) explicit instruction, (b) implicit associative learning within a computer game environment, or (c) a combination of (a) and (b) in which explicit instruction is followed by implicit learning. Our results indicated that dyslexic readers were outperformed by the controls on a time-pressured binding task and a word reading task within the artificial orthography, providing empirical support for the view that a letter–speech sound binding deficit is a key factor in dyslexia. A combination of explicit instruction and implicit techniques proved to be a more powerful tool in the initial teaching of letter–sound correspondences than implicit training alone.

Introduction

Developmental dyslexia, hereafter referred to as dyslexia, is commonly diagnosed when people unexpectedly and persistently fail to develop fluent reading skills (Fletcher & Lyon, 2008). Prevalence estimates of dyslexia typically range from 3% to 10% of the population, depending on the precise criteria used for its assessment (Snowling, 2012). The exact nature is still under debate, but the most commonly accepted hypothesis is that dyslexia is a language-based disorder that stems from a deficit in the phonological processing system (Dehaene, 2009; Vellutino, Fletcher, Snowling, & Scanlon, 2004). A subtle neurological defect that is associated with a genetic predisposition is assumed to be the underlying factor (Dehaene, 2009; Pennington & Olson, 2005; Richlan, Kronbichler, & Wimmer, 2009).

According to the phonological theory of dyslexia, a specific deficit in the representation, storage, and retrieval of speech sounds hinders the ability to attend to and manipulate them (Mattingly, 1972; Vellutino et al., 2004). Because this so-called phonological awareness is assumed to be an essential prerequisite for becoming literate, a lack of it complicates the acquisition of reading and spelling skills. However, the phonological deficit in dyslexia is not restricted to a lack of phonological awareness. Dyslexia is also characterized by disrupted rapid automatized naming of visually presented material (Denckla & Rudel, 1976; Norton & Wolf, 2012). In fact, low achievement on a task of naming a series of familiar items as quickly as possible seems to be one of the strongest predictors of dyslexia (see Norton & Wolf, 2012, for a review). The extent to which rapid naming problems are independent of other phonological problems is still debated (e.g., Vaessen, Gerretsen, & Blomert, 2009), but cross-cultural studies confirm that a combination of deficits in phonological awareness and rapid naming results in the most severely impaired reading skills (Norton & Wolf, 2012; Papadopoulos, Georgiou, & Kendeou, 2009). A third factor that has been identified as characteristic of dyslexia, and that has often been included under the umbrella of the phonological deficit, is poor verbal short-term memory (Mann & Liberman, 1984; Wagner & Muse, 2012). Typically, findings indicate that poor readers have shorter verbal memory spans on digit span tasks and nonword repetition tasks.

An important assumption of the phonological theory of dyslexia is that the phonological impairments hinder the establishment of proper letter–speech sound mappings, which is the foundation of reading alphabetic languages, resulting in disfluent word recognition. Thus, the theory provides a straightforward link between the underlying cognitive problem and the behavioral manifestation. Despite its presumed importance as a link between a phonological deficit and the reading failure that characterizes dyslexia, letter–speech sound binding has long received little attention from an empirical point of view. A dearth of research that has been counterbalanced by an increasing number of studies published during recent years (e.g., Blau et al., 2010; Blomert & Vaessen, 2009; Brem et al., 2010; Froyen, Bonte, Van Atteveldt, & Blomert, 2009). In the current study, we aimed to contribute to this emerging literature by experimentally manipulating the learning of letter–speech sound associations in typical and dyslexic readers.

Letter–speech sound mapping

In relatively transparent orthographies, such as Dutch, most children acquire the knowledge of letter–speech sound associations within approximately 1 year of formal reading instruction (Blomert & Vaessen, 2009). However, several more years of instruction and practice are needed for these associations to become fully automated (Blomert & Vaessen, 2009; Froyen et al., 2009). This process, in which learned associations between phonemes and graphemes become integrated into newly constructed audiovisual units, has been referred to as letter–speech sound binding (Blomert, 2011).

Using a mismatch negativity paradigm, Froyen et al. (2009) demonstrated that after 1 year of reading instruction, beginning readers did not show any early neural signs of letter–speech sound integration. Moreover, they found that even after 4 years of reading instruction, the integration was still not ‘‘adult-like.’’ In addition, in measuring response latencies of letter–speech sound matching, Blomert and Vaessen (2009) showed that processing speed of these associations increased systematically over the full range of primary school grades despite ceiling performance on accuracy measures from first grade onward. A comparison between typical readers and poor readers indicated that typical readers outperformed poor readers on accuracy measures only during the first 2 years of reading instruction.

On speed measures, the performance of typical readers was superior in all grades. Moreover, their response latencies decreased steadily until Grade 6. In contrast, the response latencies of dyslexic readers did not improve anymore from Grade 5 onward.

Direct evidence for disrupted letter–speech sound learning in dyslexia comes mainly from neuroimaging research. It has been demonstrated that the activity of the superior temporal sulcus is strongly associated with the neural integration of letter–speech sound pairs (Blau, Van Atteveldt, Formisano, Goebel, & Blomert, 2008; Hashimoto & Sakai, 2004; Van Atteveldt, Formisano, Goebel, & Blomert, 2004). Imaging studies revealed that in dyslexia, the activity in this region in response to letter–speech sound associations is reduced in both children and adults (Blau, Van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Blau et al., 2010).

Interestingly, Blomert and Willems (2010) found that a letter–speech sound learning problem was already present in preschool children at familial risk for dyslexia. These at-risk children did not gain from a 10-week letter–speech sound training, whereas the controls improved significantly. This indicates that although the neural integration of letter–speech sound associations is a gradual process that takes many years to fulfill, differences between dyslexic and typical readers can potentially be detected during an initial phase.

Instructional approach

Besides the wiring in the brain, reading proficiency also depends on the quality of the instruction given. Therefore, we included instructional approach as a factor in our study as well. It has been demonstrated convincingly that manipulations of educational approaches to teaching reading skill can have a substantial impact on learning outcome and on related changes in the brain (McCandliss, 2010).

In the case of dyslexia, extensive literature indicates that specialized intervention is effective in ameliorating reading and spelling proficiency and that the most effective treatment programs include (a) phonetic awareness training, (b) systematic and explicit instruction of letter–speech sound mappings, and (c) rule-based or strategy training for mastering letter–speech sound inconsistencies in words (see Singleton, 2009, for an overview). Despite the positive results of specialized intervention, it should be noted that reading rate is less susceptible to improvement than reading accuracy (Morris et al., 2012; Singleton, 2009).

Driven by the quest for new fluency-oriented remediating methods and by the knowledge from recent brain research, there is a current tendency to exchange traditional explicit techniques for implicit techniques, which are based mainly on associative learning and massive exposure and which make use of a computer game environment (Aravena & Tijms, 2009 -Chapter 2-; Lovio, Halttunen, Lyytinen, Näätänen, & Kujala, 2012; Lyytinen, 2008; Saine, Lerkkanen, Ahonen, Tolvanen, & Lyytinen, 2011). These techniques, which are particularly useful for letter–speech sound training, are implicit in the sense that learning is established not by instruction but rather by complying with the game objectives, which obviously coincide with educational aspirations. Although implicit learning plays an important role in learning to read (Gombert, 2003; Sperling, Lu, & Manis, 2004) and implicit associative techniques are promising in refining dyslexia intervention (Aravena & Tijms, 2009 -Chapter 2-; Lovio et al., 2012; Lyytinen, 2008; Saine et al., 2011), we need to be cautious of throwing the baby out with the bathwater by abandoning explicit instruction. It is assumed that the development of explicit and systematic decoding skills acts as a bootstrapping mechanism for further implicit learning (Aravena & Tijms, 2009 -Chapter 2-; Gombert, 2003; Share, 1995). This idea is supported by more general accounts of skill acquisition in which controlled metacognitive processing typical of novice performance is gradually being replaced by automatic associative processes with growing expertise (Chein & Schneider, 2005; Siegler, 2005).

Clinical evidence for the interplay between initial explicit and subsequent implicit processes comes from research by Tijms (2007). His data revealed that during the first half of traditional dyslexia intervention, most progress was made on reading accuracy, which gradually turned over into a more prominent development of reading rate during the second half of intervention. Moreover, in contrast to reading accuracy, reading rate continued to develop after termination of the intervention.

The current study

In our study, dyslexic and typical readers engaged in a short training aimed at learning eight basic letter–speech sound correspondences within an artificial orthography. The script was artificial in the sense that unfamiliar letters (Hebrew) were used to transcribe participants' native language (Dutch). By this means, we were able to compare the initial steps of dyslexic and typical readers in learning a novel script. If individuals with dyslexia have a deficit for learning letter–speech sound associations, we would expect them to be at a disadvantage right from the start when getting familiar with a new set of letter–speech sound correspondences.

One advantage of adopting an artificial script is that it allows for precise control over the input. Differences in previous exposure to experimental stimuli can be ruled out, allaying concerns about noncontrolled factors influencing performance. Hence, the artificial script paradigm is especially useful for exploring phenomena associated with the early phases of learning to read in children that are already literate to some extent.

In contrast to previous behavioral studies that yielded evidence for deficits in letter–speech sound learning in dyslexia, such as the aforementioned studies by Blomert and Vaessen (2009) and Blomert and Willems (2010), in the current study we were able to control completely for differences in exposure to the concerned letter–speech sound correspondences. Moreover, by using the artificial script, we were able to study letter–speech sound learning in dyslexic readers at different ages, taking away the necessity of using preliterate children at familial risk for dyslexia. Thus, an artificial script provides a powerful tool for studying letter–speech sound learning in individuals with dyslexia and for extending the literature on the etiology of dyslexia. Only a few studies have addressed letter–speech sound learning within an alphabetic artificial orthography (Hashimoto & Sakai, 2004; Maurer, Blau, Yoncheva, & McCandliss, 2010; Taylor, Plunkett, & Nation, 2011; Yoncheva, Blau, Maurer, & McCandliss, 2010). To our knowledge, the current study is the first to focus on letter–speech sound learning within an artificial orthography with dyslexic readers.

To evaluate the influence of an instructional approach, we assigned children from both groups to one of three different training conditions: (a) explicit instruction,

(b) implicit associative learning within a computer game environment, or (c) a combination of (a) and (b) in which explicit instruction is followed by implicit learning. Both letter knowledge and word reading ability within the artificial script were assessed during the training session.

Most writing systems also include nonstandard letter–speech sound correspondences, producing spelling patterns that depend on syllabic, morphological, or syntactic structure. To master these correspondences, children are taught explicit spelling rules at school, although there is evidence that beginning readers also capitalize on implicit mechanisms while learning spelling rules (Cassar & Treiman, 1997; Kemp & Bryant, 2003; Pacton, Perruchet, Fayol, & Cleeremans, 2001; Wright & Ehri, 2007). For example, Cassar and Treiman (1997) found that young children had knowledge of which letters can be doubled in English without being taught the corresponding rule. To capture the characteristics of natural language, we also included a spelling rule in the artificial orthography. We were interested to see whether there are signs of implicit learning of nonstandard correspondences within the initial steps of learning a novel script.

Because the current study uses an artificial script paradigm, findings can have practical implications only if we can translate them to reading skills in the real world. Therefore, we also examined whether reading proficiency in the trained script correlated with the typical reading skills learned at school.

In summary, in the current study, we examined whether disrupted letter–speech sound learning is behaviorally detectable within the initial steps of learning a novel script and whether there are differences between dyslexic readers and the controls in the ability to read the novel script after a short letter–speech sound training. In addition, we assessed whether differences in instructional approach lead to differences in learning outcome. Finally, we evaluated the validity of our results by correlating reading proficiency in the trained novel script with reading proficiency in the orthography belonging to the native language.

Methods

Participants

Our sample consisted of 62 children (35 boys and 27 girls) diagnosed with dyslexia and 64 children (31 boys and 33 girls) with average or above average reading and spelling skills. The children diagnosed with dyslexia were recruited from the IWAL Institute, a nationwide center for dyslexia in The Netherlands. The nonimpaired readers were selected from the same sample of schools as the dyslexic readers to control for socioeconomic status (SES), demography, and education. The age range spanned from 7.5 to 12.4 years. All participants were primary education pupils and were native speakers of Dutch. We obtained informed consent from all of the parents involved. The study was approved by the ethics committee of the University of Amsterdam. Participant characteristics are shown in Table 1. No significant baseline differences in age, intelligence, or vocabulary were found between the two reading groups (all *ps* > .05).

Table 1:
Participant characteristics by reading group and training condition

	Dyslexic (*n*=62)						Control (*n*=64)					
	EXP (*n*=21)		IMP (*n*=21)		COM (*n*=20)		EXP (*n*=20)		IMP (*n*=21)		COM (*n*=23)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age	9,79	1,02	9,71	1,05	9,65	0,83	9,77	0,78	9,89	1,19	9,95	1,00
IQ	6,81	2,04	6,53	2,00	6,47	1,68	7,30	2,08	6,95	1,88	7,26	2,09
Vocabulary	6,10	1,18	6,05	1,69	5,85	1,66	6,40	1,19	6,05	1,28	6,91	1,44

Note: EXP, explicit condition, IMP, implicit condition, COM, combined condition

Selection criteria

Selection of the dyslexic group was based on criteria for severe dyslexia in the Dutch health care system (Blomert, 2006), implying that children had a severe and persisting reading problem in combination with a phonological deficit. Inclusion of a causal factor provides the possibility to select a homogeneous sample, making generalization and replication of results possible (Torgesen et al., 1999). More specific, children were selected for the study if they met all of the following three inclusion criteria: (a) either word reading rate of 1.5 standard deviations or more below average or word reading rate of at least one standard deviation below average together with a spelling skill of 1.5 standard deviations or more below average, (b) performance on at least two of six administered phonological tasks (i.e., grapheme–phoneme identification task accuracy and speed, phoneme deletion accuracy and speed, and rapid naming of numbers and letters) that was at least 1.5 standard deviations below average; and (c) poor response to intervention provided at school. Exclusion criteria were uncorrected sensory disabilities, broad neurological deficits, insufficient education, and attention deficit/hyperactivity disorder (ADHD). Because we incorporated Hebrew graphemes into our artificial orthography, previous experience with Hebrew script was also an exclusionary criterion. Allocation to the control group was based on the school record. We selected normal achieving children within general education. Children were selected only if both their reading and spelling scores were above the 25th percentile.

Artificial orthography

The artificial orthography consists of eight Hebrew graphemes that are randomly matched to Dutch phonemes, thereby providing eight basic letter–speech sound pairs. Because evidence exists that letter shapes are not an arbitrary cultural choice but rather a product of our neural architecture (Dehaene, 2009, p. 173), we adopted Hebrew script to capture the characteristics of graphemes as they naturally occur. The script represents four vocals and five consonants. Combinations of phonemes producing strong coarticulation effects were avoided. Table 2 displays an overview of the letter–speech sound correspondences that were used. The directionality of the script is left to right.

Table 2:
Letter-speech sound correspondences within an artificial orthography

Letter	ט	כ	ם	ף	פ	צ	ך	ש
Speech sound (IPA)	[u]	[ɛ]	[ɑ] [a]	[k]	[r]	[l]	[t]	[n]

Note: IPA, International Phonetic Alphabet

From the corpus of words that could be created by combining the nine chosen phonemes, we selected 116 high-frequent Dutch monosyllabic words of which 86 words were used for training purposes. The remaining 30 words were used for the word reading assessment. Thus, by using other words for training purposes rather than for assessment, the current study was designed to find transfer of learning by ruling out the possibility that words from the training were recognized without decoding. We composed an additional set of 52 pseudowords that were also used for training purposes. All pseudowords obeyed Dutch phonotactic regularities. One letter (ם) in our artificial orthography was ambiguous because it corresponded with both the short vowel /ɑ/ and the long vowel /a/. Correct interpretation of this letter could be obtained only by applying the following rules:

1) A short vowel /ɑ/ is followed by a consonant that is written with a single grapheme (ךםף).
2) A long vowel /a/ is followed by a consonant that is written with a double grapheme (ךםףף).

Training methods

Children in both groups participated in a single session, during which two 30-min training blocks (A and B) were employed for either explicit or implicit training. Both training approaches are outlined below.

Explicit instruction approach

The explicit training we developed was based on specialized dyslexia treatment as it is employed in clinical practice nowadays (see Singleton, 2009, for an overview), implying that all exercises were aimed at systematic instruction of phonological structure and letter–speech sound mapping combined with rule-based training for mastering letter–speech sound inconsistencies in words. We provided the trainer with a protocol to ensure standardization of instruction. At the start of Block A, children were told that they were engaging in a task where they would be learning a secret code. During the training, we used software containing several exercises designed to give pupils explicit insight into the way letters and speech sounds correspond. The exercises were guided by the experimenter's verbal instruction. First, all letter–speech sound correspondences were introduced one by one. To support retention, speech sounds were linked to words, which in turn were represented by images. In Figure 1, for example, the letter פ is matched with the speech sound /r/ and is supported by an image of the Dutch word roos ('rose') that starts with /r/.

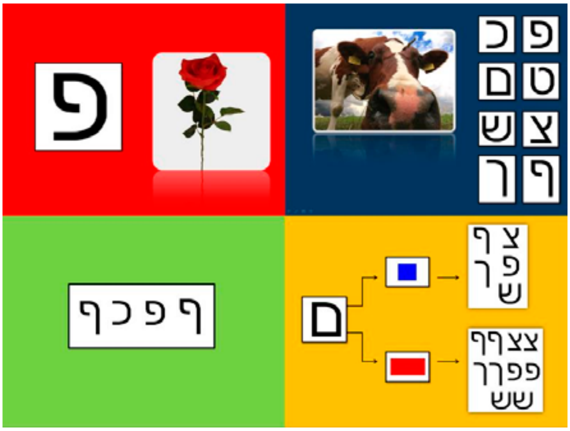


Figure 1 Screenshots from explicit training

Subsequently, children needed to compose words dictated by the experimenter using a small keyboard displayed on the screen. On a keystroke, the corresponding sound was presented simultaneously through a speaker. The arrangement of the keyboard differed with every item to avoid spatial learning. Figure 1 depicts an example of this exercise in which the stimulus is the Dutch word koe ('cow'). Finally, children were presented with a sequence of letters and needed to blend the corresponding speech sounds to form words (Figure 1). After approximately 20 min, the experimenter presented the orthographic rule with the aid of the plan displayed in Figure 1. During the remainder of the block, exercises that contained words both with and without the rule were repeated. In contrast to the associative training condition in which fast playing was encouraged, there was no time pressure during explicit instruction. Block B of the explicit training contained similar exercises as Block A. No additional instruction was given. In contrast to Block A, Block B also included pseudowords. Three additional exercises were introduced in Block B: an exercise with shuffled letters that needed to be rearranged into words, an exercise in which all letters were fading away while children needed to recall the position in response to a presented speech sound, and a memory span exercise in which children needed to repeat back orally a progressively larger sequence of letters. Although some of the exercises in Block B had limited stimulus exposure, response time again was unlimited.

Associative instruction approach

For the implicit associative training, we employed a computer game in which children needed to match speech sounds to their corresponding orthographic representations. Correct associations led to success in the game, whereas incorrect associations jeopardized a positive outcome. Fast playing was reinforced by progressive time restrictions and by providing bonuses for fast playing. More specific, children operated a cannon at the bottom of the screen, moving it horizontally. The upper part of the screen was composed of columns of balloons containing single letters or words. Children were required to act on speech sounds that were presented repeatedly in the game. The response consisted of releasing bullets from the cannon and associating them to their corresponding orthographical representations. When children managed to clear a field of balloons, a new field was presented. Because fields became increasingly more complex and children needed to succeed in order to progress in the game, the training is adaptive in nature. Figure 2 depicts some screenshots from the game.

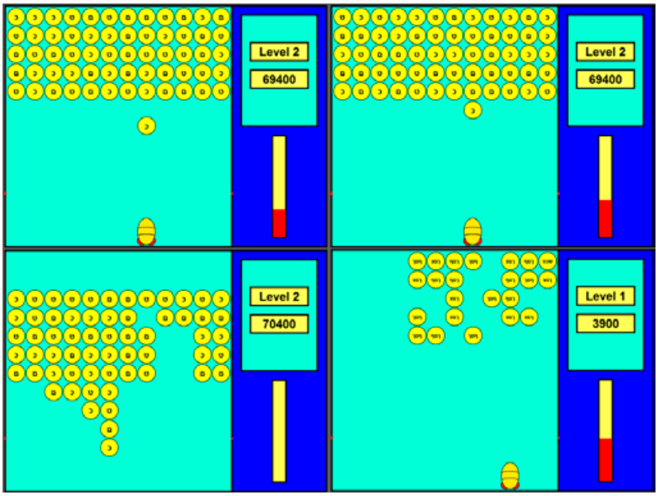


Figure 2 Screenshots from implicit training

At the start of Block A, children were presented with a standardized instruction that is integrated in the software. This instruction clarified the specifics of the game but did not reveal the underlying learning objective. All fields in Block A contained single-letter stimuli. In Block B, some balloons contained single letters, whereas others contained words. This change was introduced by an additional instruction at the start of Block B. In Block B, some fields included words that could be deciphered successfully only by applying the orthographical rule, giving children the opportunity to learn the rule.

After the instruction, children received a short practice trial to become familiar with the setup and the controls of the game. For children in the combined condition, this trial followed the instruction introducing Block B. During the training session, children wore headphones.

Outcome measures

We included seven outcome measures in our study. Four of them were used for assessing the effects of the training. One measure was included to relate the training effects to the actual Dutch reading skills. The two other measures were used to control for differences in general intelligence and vocabulary. An overview of the outcome measures is provided below.

Letter knowledge

We used four identical evaluation forms (EF 1–4) for assessing letter knowledge. The experimenter presented children with the form containing the eight letters. While pointing at one of the letters, the experimenter asked children to name the letter and wrote down the answer. For the retention task at home, each child's parents took over the role of the experimenter. For each of the forms, the score was determined by the number of speech sounds that were named (maximum = 9).

Error rate within computer game

The amount of errors during the implicit training was recorded automatically by the software. The score was expressed as the total number of errors divided by the total number of items. Because this measure applies exclusively to the implicit training, data were taken only from Block B of the implicit and combined conditions.

Word reading rate in artificial orthography

We administered a lab-created time-limited test (3MAST) consisting of a list of 30 high-frequent Dutch words written within the artificial orthography. The words were presented in lowercase Arial typeface, font size 24, and arranged in two columns of equal length. Children needed to read as many words as possible within 3 min. Words were arranged with increasing complexity. The score was determined by the number of words read correctly per second.

Mastery of orthographic rule

We used a dichotomous measure based on the 3MAST reading test to assess mastery of the spelling rule. From the list of 30 words, eight words required the application of the orthographic rule for reading them correctly. When children managed to apply the rule properly in all words read within the time limit, it was considered an acknowledgment of mastery.

Word reading rate in Dutch

We used the One-Minute Test (Brus & Voeten, 1973), a time-limited test consisting of a list of 116 unrelated words of increasing difficulty, for assessing word reading skills in Dutch. The score was determined by the number of words read correctly within 1 min (r = .89–.93, test–retest).

Intelligence measure

General intelligence was assessed by the Analogies subtest from the SON-R (Snijders–Oomen Nonverbal test; Laros & Tellegen, 1991), a nonverbal reasoning-by-analogy task in which children need to extract a principle and apply it to a new situation (r = .79, test–retest).

Vocabulary

Vocabulary was assessed by the Vocabulary subtest from the WISC-III (Wechsler Intelligence Scale for Children; Kort et al., 2005), a measure of expressive vocabulary in which children needed to describe the meanings of words of increasing complexity (*r* = .90, test–retest).

Procedure

As mentioned before, the session consisted of three 30-min blocks; the first two blocks served as the training, whereas the third block was devoted to administering a short intelligence test and a vocabulary test. After each block, we evaluated letter knowledge by presenting children visually with the eight letters and asking them to name the corresponding sounds. This evaluation task was repeated at home 1 week after the training session to measure retention of letter knowledge. Accordingly, we instructed parents to conduct the task and to send back filled-in companion forms. After the second evaluation of letter knowledge, when both training blocks were completed, we administered a single-word reading task containing words written in the artificial orthography. Figure 3 depicts an overview of the entire session, including the retention measure.

Block A	EF1	Block B	EF2	Block C	EF3	Interval	EF4
30 minutes		*30 minutes*		*30 minutes*	&	*1 week*	
Explicit or implicit training		Explicit or implicit training		Intelligence & vocabulary assessment	3MAST		

Figure 3 Session overview. Note: EF, letter knowledge assessment within artificial script, 3MAST, reading assessment within artificial script

All participants completed the entire session. We were able to use data from 97 of 126 filled-in companion forms for the 1-week retention measure. Data from the other 29 forms were missing due to noncompliance. For most cases of noncompliance, parents exceeded the 1-week term for administering the evaluation.

All three blocks were provided on a one-to-one basis in a silent room. The nonimpaired readers attended their session in the school building. The dyslexic readers were invited to the nearest branch of the dyslexia institute from which they were recruited. For both the explicit and implicit training, we used an Acer Aspire 5500Z 14,1-inch laptop computer in full-screen mode. The total duration of the session was approximately 100 min.

Results

Preliminary analyses with age and IQ as covariates did not change the pattern of findings reported below.

Letter–speech sound binding deficit

To determine whether a letter–speech sound binding deficit was manifest in dyslexic readers while learning a novel script, we first compared the scores of both groups on the evaluation task of letter knowledge administered at four different moments (EF 1–4: halfway training, end training, 30-min follow-up, and 1-week follow-up, respectively). We used a generalized linear model based on ordinal logistic regression consisting of group (dyslexia or control), condition (explicit, implicit, or combined), and time (EF 1, 2, 3, or 4) as factors and letter knowledge as a dependent variable. By this means, differences in learning outcome due to differences in instructional approach were taken into account within the same model. The mean scores and standard deviations obtained are shown in Table 3.

Analysis revealed a significant main effect for condition, Wald chi-square = 97.34, $p < .0001$, with a medium to large effect size ($w = .45$), and for time, Wald chi-square = 33.18, $p < .0001$, with a medium effect size ($w = .26$). Importantly, the model indicated that letter knowledge was significantly lower after the associative training than after both the explicit and combined training. The time effect revealed that letter knowledge was significantly higher when assessed after Block B (end training) and Block C (30-min follow-up) than after Block A (halfway training) and the 1-week follow-up.

Table 3:
Means and standard deviations for letter knowledge

	Dyslexic						Control					
	EXP		IMP		COM		EXP		IMP		COM	
	M (SD)	*n*	*M (SD)*	*n*	*M (SD)*	*n*	*M (SD)*	*n*	*M (SD)*	*n*	*M (SD)*	*n*
EF1	8.05 (0.38)	21	6.05 (1.75)	21	7.55 (0.95)	20	7.85 (0.49)	20	5.14 (1.49)	21	7.70 (0.88)	23
EF2	8.00 (0.32)	21	6.33 (1.74)	21	7.50 (0.95)	20	8.00 (0.00)	20	6.29 (1.31)	21	7.91 (0.67)	23
EF3	8.00 (0.00)	21	6.38 (2.01)	21	7.80 (0.89)	20	8.00 (0.00)	20	6.38 (1.24)	21	7.91 (0.67)	23
EF4	7.62 (0.62)	16	5.94 (1.95)	16	7.30 (1.06)	10	7.81 (0.40)	16	5.76 (1.15)	17	7.59 (1.05)	22

Note: EXP, explicit condition, IMP, implicit condition, COM, combined condition, EF, letter knowledge assessment within artificial script

Table 5:
Means and standard deviations for reading within the artificial orthography

	Dyslexic						Control					
	EXP		IMP		COM		EXP		IMP		COM	
	M (SD)	*n*	*M (SD)*	*n*	*M (SD)*	*n*	*M (SD)*	*n*	*M (SD)*	*n*	*M (SD)*	*n*
WPS	0.16 (0.06)	21	0.05 (0.03)	21	0.11 (0.06)	20	0.17 (0.04)	20	0.06 (0.04)	21	0.16 (0.07)	23
WPS 100%	0.16 (0.06)	20	0.07 (0.02)	8	0.14 (0.04)	15	0.17 (0.04)	20	0.12 (0.02)	5	0.17 (0.06)	22

Note: EXP, explicit condition, IMP, implicit condition, COM, combined condition, WPS, words read per second

We did not find main effects for group, Wald chi-square = .11, p = .74, or significant interactions between group and condition, Wald chi-square = 3.14, p = .21. Thus, the results show that disrupted letter–speech sound binding was not manifested through differences in basic letter knowledge after training. The new correspondences were learned quite easily by most of the participants, and no differences were found between dyslexic readers and controls.

A second analysis concerned the error rate during the implicit training. Applying the knowledge of the newly learned correspondences in game play imposes much higher demands on the quality of these correspondences. Because error rate applies exclusively to the implicit training, a comparison could be made only between the implicit and combined conditions. The mean scores and standard deviations obtained are shown in Table 4. We conducted a two-way analysis of variance (ANOVA) with group (two levels) and condition (two levels) as factors. Because we were dealing with proportional data with a binomial distribution, we applied an arcsine transformation to stabilize the variance.

Table 4:
Means and standard deviations for error rate during training

	Dyslexic				Control			
	IMP		COM		IMP		COM	
	M (SD)	*n*	*M (SD)*	*n*	*M (SD)*	*n*	*M (SD)*	*n*
Error rate	0.31 (0.11)	20	0.23 (0.08)	20	0.24 (0.06)	23	0.18 (0.08)	21

Note: IMP, implicit condition, COM, combined condition

We found significant main effects for group, $F(1,80) = 10.02$, $p < .01$, with a medium to large effect size (partial η^2 = .11), and for condition, $F(1,80) = 15.54$, $p < .0001$, with a large effect size (partial η^2 = .16). In both conditions, dyslexic children made significantly more errors during training than the controls. Furthermore, both groups made fewer errors after 30 min of explicit training than after 30 min of associative training. No interaction effect was found, $F(1,80) = .07$, $p = .79$. The results indicate that during training, when speech sounds needed to be matched to their corresponding letters under pressure of time, dyslexic children were more prone to errors than the controls. Accordingly, this finding points to an early manifestation of disrupted letter–speech sound binding.

From binding deficit to reading problems

If the higher error rate during the implicit training represents a letter–speech sound binding deficit, we also would expect children with dyslexia to be at a disadvantage when it comes to reading the novel script. To determine whether there were differences between dyslexic readers and the controls in the ability to read the novel script after a short letter–speech sound training, we conducted a two-way ANOVA with group (two levels) and condition (three levels) as factors. The mean scores and standard deviations obtained are shown in Table 5.

Analyses revealed significant main effects for group, $F(1,120) = 7.88$, $p < .01$, with a medium effect size (partial $\eta^2 = .06$), and for condition, $F(2,120) = 51.36$, $p < .0001$, with a large effect size (partial $\eta^2 = .46$). The controls read significantly more words per second than the dyslexic children. The Helmert contrast indicated that the amount of words read per second was significantly lower after the associative training than after both the explicit and combined training ($p < .0001$). Furthermore, it showed that the amount of words read per second was also significantly lower after combined training than after explicit training ($p < .05$). No significant interaction effect was found between group and condition, $F(2,120) = 2.05$, $p = .13$.

Because letter knowledge is a basic requirement for obtaining reading proficiency, and differences in word reading could be due to differences in letter knowledge, we also conducted analyses on the sample of children who reached full mastery of the letter–speech sound associations within the artificial orthography. After 60 min of training, 71.4% of participating children (73.4% of dyslexic readers and 69.4% of controls) reached complete mastery of the letter–speech sound associations within the artificial orthography; that is, they correctly matched all eight speech sounds to their corresponding letters (or even to nine when children spontaneously executed the rule). A Pearson’s chi-square analysis showed no significant difference between the dyslexic and control groups, $\chi^2(1) = .26$, $p = .70$. Additional analyses on this sample revealed that the results are slightly more pronounced when full mastery is required. Table 5 displays means and standard deviations. Again, significant main effects were found for group, $F(1,84) = 8.20$, $p < .01$, with a medium effect size (partial $\eta^2 = .09$), and for condition, $F(2,84) = 9.43$, $p < .0001$, with a large effect size (partial $\eta^2 = .18$). Controls outperformed dyslexic readers on the reading task, and the Helmert contrast indicated that the amount of words read per second was significantly lower after the associative training than after both the explicit and combined training ($p < .0001$). The current results indicate that typical readers read substantially faster than children with dyslexia after just 1 hour of training in the novel orthography. This finding could not be explained by differences in letter knowledge because differences between typical and dyslexic readers were also manifest when only children with complete mastery were included.

Rule knowledge

To test whether instructional approach predicted the proper application of the orthographic rule, we compared rule mastery on the 3MAST reading test after each of the three conditions. A Pearson's chi-square showed that there was a significant association between instructional approach and mastery of the orthographic rule during the reading task, χ^2 (2) = 64.566, $p < .01$. This seems to represent the fact that, based on the odds ratio, the odds of applying the rule were more than 100 times higher after explicit training than after associative training and were more than 20 times higher after combined training than after associative training. In fact, none of the children from the associative training condition was able to deduce the orthographical rule by himself or herself. Thus, the explicit component of the training seems to be of decisive importance for mastering the orthographic rule. We found a small, but nonsignificant, difference in rule mastery between the dyslexic readers and the controls. After training, 66.1% of children with dyslexia and 76.6% of the controls showed mastery of the orthographic rule during the reading task.

Reading in artificial orthography versus reading in natural language

To compare reading proficiency in the trained script with the typical reading skills learned at school, we conducted a Pearson correlation (two-tailed) within the dyslexic group. Because letter knowledge is a basic requirement for obtaining reading proficiency, in the analyses we included only children who reached full mastery of the letter–speech sound associations within the artificial orthography (N = 42). A significant correlation was found between reading rate (words per second) in the artificial orthography and reading rate in Dutch, the natural language of the children participating in this study (r = .52, p < .0001). This result supports the external validity of our study and thereby seems to legitimize generalizations of our main findings to reading in natural languages.

Discussion

In the current study, we focused on the initial development of letter–speech sound associations, the first crucial step in reading development. Because our study is the first to address the initial phase of letter–speech sound learning in dyslexia by using an artificial orthography, we can report several interesting findings.

Our results indicated differences between typical readers and dyslexic readers during the first stages of learning letter–speech sound correspondences, providing empirical support for the view that a letter–speech sound binding deficit is a key factor in dyslexia (Blau et al., 2009, 2010; Blomert, 2011; Blomert & Vaessen, 2009). In line with previous findings, we did not find differences in basic letter knowledge after a short training. Most of the children in both the dyslexic and control groups learned the new correspondences relatively fast and were able to name the letters correctly. We did find evidence for disrupted letter–speech sound learning in dyslexia, however, when children needed to apply their knowledge of these correspondences in more complex tasks. When during training speech sounds needed to be matched to their corresponding letters under time pressure, the children with dyslexia were more prone to errors than the controls. Moreover, the controls outperformed the children with dyslexia on a word reading task containing familiar words written in the artificial orthography. It is important to note that the differences we found between dyslexic and typical readers were independent of letter knowledge.

By adopting an artificial orthography, we were able to extend previous results with regard to some important issues. In the Blomert and Vaessen (2009) study, where letter–speech sound processing was explored throughout primary school, it was difficult to control for the interplay among letter–speech sound learning, phonological development, and reading development. It is possible that the typical readers outperformed the poor readers on speed measures as a consequence, rather than as a cause, of reading disabilities. In the Blomert and Willems (2010) study, this problem was remedied by using a sample of preliterate children at risk for dyslexia. But because training took place within the first half year of reading instruction at school, potential differences in exposure between the groups still could not be excluded. Reading circumstances could have been different for children from a family with a sibling diagnosed for dyslexia. In the current study, we were able to rule out potential differences in prior exposure to experimental stimuli and to show that individuals with dyslexia carry a binding deficit with them and that this deficit is manifested at any time when presenting them with a novel script.

An additional goal of the current study was to investigate the influence of instructional approach on the initial learning of letter–speech sound correspondences. We were specifically interested in the role of implicit training techniques because they might induce automation of letter–speech sound processing. Because children started the training without any previous knowledge of the script, and more than two thirds of them knew all correspondences afterward, the findings clearly indicated that both the explicit and implicit training we provided resulted in learning. Importantly, the implicit training ended in less learning progress than both the explicit training and the combined training. This finding suggests that at least some explicit preparation is necessary before implicit training becomes effective. Implicit training without explicit preparation resulted in less letter knowledge, a higher incidence of errors when engaging in the game, and a lower reading rate within the trained orthography. Again, the lower reading rate was also found independent of letter knowledge.

From a qualitative perspective, and focusing exclusively on explicit versus implicit techniques, we can conclude from our findings that there are no differences in educational needs between dyslexic readers and typical readers. The relative failure of isolated implicit training applies to both groups. Nevertheless, the finding that both groups can benefit from a combined instructional approach is particularly valuable for dyslexic readers because they are in strong need of print exposure. Not only do they need to make up for the considerable deficits in reading practice they have accumulated over time (Torgesen, 2005), but experimental studies also confirm that children with dyslexia need much more exposure to learn words by sight (e.g., Thaler, Ebner, Wimmer, & Landerl, 2004). Adding implicit training to explicit instruction is an efficient way of optimizing exposure, taking into account the limits of cognitive load.

These results are interesting in relation to the current focus on implicit techniques that capitalize on computer game environments within dyslexia intervention (Aravena & Tijms, 2009 -Chapter 2-; Lyytinen, 2008; Saine et al., 2011). These so-called 'edugames' were brought into action in the quest for new fluency-oriented intervention. Because they offer the possibility to establish massive exposure within a highly motivational environment and without high demands for cognitive load, they might be particularly suitable for dyslexia intervention. The findings of the current study indicated, however, that a combination of explicit instruction and implicit techniques provides a more powerful tool in the initial teaching of letter–sound correspondences than implicit training alone. The results concerning the acquisition of rule knowledge in relation to the instructional approach are crystal clear. None of the children engaging solely in the edugame was able to deduce the orthographical rule by himself or herself. Evidently, to be able to apply an algorithmic spelling rule in reading, at least some portion of explicit instruction is needed, or much more time is needed, for implicit learning to come about. This finding is in line with previous results indicating that implicit learning of spelling rules may depend largely on sensitivity to the frequency with which certain combinations of letters occur (e.g., Kemp & Bryant, 2003). Distributional features of the input can be detected only if there is a sufficient amount of exposure. It seems that, in general, children need a great deal of time to master spelling rules at school (Hilte & Reitsma, 2011; Kemp & Bryant, 2003). Thus, studying spelling rule acquisition at the lab, as in the current study, may require much more time or the use of a simpler rule structure.

Limitations, prospects, and practical implications

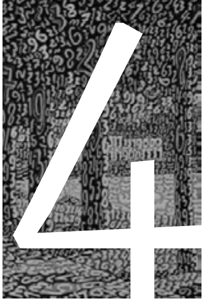
We adopted an artificial orthography paradigm, assuming that by this means we were able to rule out differences in previous exposure to experimental stimuli. A limitation of the current study is that the children still needed to transcribe phonemes from their native language. Therefore, we cannot rule out the possibility that dyslexic readers were put at a disadvantage at the start of the session due to a less well-specified phonemic framework; consequently, we cannot establish a cause–effect relationship between disrupted letter–speech sound binding and a deficit in phonological processing. For future research, it would be of interest to focus on further positioning this binding deficit within the etiological framework of dyslexia. The current view is that disrupted letter–speech sound binding results from a phonological deficit, but because this assumption has not been confirmed experimentally, room for alternate views remains. In fact, in two studies the development of letter–speech sound associations was found to be independent of prior phonological or orthographical knowledge (Blomert & Willems, 2010; Castles, Coltheart, Wilson, Valpied, & Wedgwood, 2009). It has even been proposed that a letter–speech sound binding deficit in itself might be the proximal cause of dyslexia (Blau et al., 2009, 2010; Blomert, 2011; Wallace, 2009). Thus, future research should further explore how letter–speech sound mapping relates to other phonological skills and whether a letter–speech sound binding deficit as a predictor of reading problems also occurs independent of a phonological deficit. An appealing avenue would then be to measure letter–speech sound binding abilities within a group of preliterate children, including children carrying a familial risk for dyslexia, and to test whether these abilities make a unique contribution in predicting future reading and spelling skills compared with typical phonological and orthographical predictors. Another way to further explore the nature of a letter– speech sound binding deficit and its relation to phonological skills is to assess letter–speech sound binding in children with reading disabilities who do not show any phonological deficit. If these children do less well than typical readers, that would indicate that this binding deficit can also manifest itself in the absence of a phonological deficit.

In addition to the relation between letter–speech sound binding and typical phonological skills, it would also be of interest to focus on possible correlations with other cognitive abilities, especially those that have been linked to dyslexia in previous studies such as sensitivity to statistical regularities (Pavlidou, Kelly, & Williams, 2010) and visual attention (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012). There might be more cognitive deficits that are associated with hampered letter–speech sound binding.

Another limitation of our study is that learning letter–speech sound correspondences for a second time within the same language may involve different learning mechanisms than letter–speech sound learning the first time. Interestingly, imaging studies within the artificial orthography paradigm indicated that brain changes occurring during the learning of a novel script seemingly parallel the changes that took place during the first encounter with an already familiar script (Hashimoto & Sakai, 2004; Maurer et al., 2010). Nevertheless, we need to be cautious in generalizing the current findings to the natural process of learning letter–speech sound correspondences for the first time.

Finally, our findings may have implications for assessment. The fact that differences in letter–speech sound learning can be detected during an initial phase provides opportunities for designing more process-oriented diagnostic tools. Currently, there is a paucity in our knowledge of factors that predict responsiveness to dyslexia intervention (Frijters et al., 2011; Hoeft et al., 2011; Tijms, 2011). Process-oriented diagnostic tools that focus on learning are potentially capable of predicting future reading gains in dyslexia intervention. In future research, it would be interesting to reshape the training used in the current study into a practical diagnostic tool. Accordingly, one could examine from which age onward differences in letter–speech sound learning can be detected by this tool. Because it can be applied independent of phonological or reading instruction, it might be adequate for preschoolers as well, providing opportunities for early detection of dyslexia.

In summary, our results contribute to the understanding of the etiology of dyslexia. We found convincing behavioral evidence for disrupted letter–speech sound learning in dyslexia. With the use of an innovative experimental design with an artificial orthography, we were able to see letter–speech sound learning in action at our lab. Our results indicated that learning difficulties within this domain can be manifested at any time and that they cannot be attributed to differences in prior exposure to the concerned correspondences. Importantly, we also found evidence that disrupted letter–speech sound binding immediately affects reading performance irrespective of letter knowledge. Moreover, in support of the external validity of our study, the results indicated that reading proficiency in Dutch was correlated with reading proficiency in the artificial script. Together with other recent findings regarding letter–speech sound learning in dyslexia, our results invite a more prominent role for letter–speech sound learning within the etiological framework of dyslexia. We hope that our innovative design will inspire new research applying the artificial orthography paradigm to further elucidate the nature of letter–speech sound binding and its relation to phonological processing and reading development.



4

CHAPTER

Predicting individual differences in reading and spelling skill with an artificial script-based letter-speech sound training

Aravena, S., Tijms, J., Snellings, P., & van der Molen, M. W. (in press). Predicting individual differences in reading and spelling skill with an artificial script-based letter-speech sound training. *Journal of Learning Disabilities.*

Abstract

In this study we examined the learning of letter-speech sound correspondences within an artificial script and performed an experimental analysis of letter-speech sound learning in dyslexic and typical readers vis-a-vis phonological awareness, rapid automatized naming, reading, and spelling. Participants were provided with a 20-minute training aimed at learning eight new basic letter-speech sound correspondences, followed by a short assessment of both mastery of the correspondences and word reading ability in this unfamiliar script. Our results demonstrated that a brief training is moderately successful in differentiating dyslexic readers from typical readers in their ability to learn letter-speech sound correspondences. The typical readers outperformed the dyslexic readers on both accuracy and speed on a letter-speech sound matching task, as well as on a word reading task containing familiar words written in the artificial orthography. Importantly, the new artificial script-related measures were related to phonological awareness and rapid automatized naming and made a unique contribution in predicting individual differences in reading and spelling ability. Our results are consistent with the view that a fundamental letter-speech sound learning deficit is a key factor in dyslexia.

Introduction

Developmental dyslexia, henceforth referred to as dyslexia, is a disorder that is characterized by disfluent and inaccurate reading that cannot be attributed to low intellectual ability, poor education, or sensory disabilities (Lyon, Shaywitz, & Shaywitz, 2003). Prevalence estimates range from 3% to 10%, depending upon the language and the precise criteria used for its assessment (Snowling, 2012). Dyslexia is generally considered a language-based disorder that stems from a deficit in the phonological processing system (Dehaene, 2009; Peterson & Pennington, 2015). It still remains to be elucidated exactly how this phonological deficit leads to reading difficulties, but a prevailing view is that poor phonological awareness results in reading problems because it hinders the formation of proper letter-speech sound mappings, which is the foundation of reading alphabetic languages (e.g. Peterson & Pennington, 2012; Snowling, 2012).

Research has focused primarily on identifying and understanding the specific phonological shortcomings in dyslexic readers. Surprisingly, the formation of letter-speech sound mappings has long received little attention from an empirical point of view, but during the past few years this topic has been the focus of growing interest (Hahn, Foxe, & Molholm, 2014; Jones, Kuiper, & Thierry, 2016; Peterson & Pennington, 2015; van Atteveldt & Ansari, 2014). In the current study we extend this research by examining letter-speech sound learning within an artificial script, focusing on its potential to differentiate between dyslexic readers and typical readers, its contribution to individual differences in reading and spelling skills, and its relation to the phonological shortcomings typically found in dyslexia.

Recent studies, including studies with a cross-linguistic design, substantiate that dyslexic readers typically experience difficulties within two broad phonology-related domains, namely phonological awareness (PA) and rapid automatized naming (RAN) (Boets et al., 2010; Landerl et al., 2013; Ramus & Ahissar, 2012). The former refers to the ability to identify and manipulate speech sounds and is usually assessed by tasks in which speech sounds have to be segmented, blended, replaced or deleted. An extensive body of research demonstrates that poor PA is one of the strongest correlates associated with reading and spelling disabilities (see Melby-Lervåg, Lyster, & Hulme, 2012 for a review). The latter, RAN, involves naming a series of familiar visually presented items, such as alphanumeric items, colors or objects, as quickly as possible (Denckla & Rudel, 1976). Poor achievement on RAN tasks is one of the strongest predictors of dyslexia (see Norton & Wolf, 2012, for a review). Findings indicate that 60% to 75% of individuals with a reading disability also exhibit a RAN deficit and that this deficit is present before reading instruction commences (Norton & Wolf, 2012). The double deficit hypothesis (Wolf & Bowers, 1999) further claims that PA and RAN contribute separately to reading ability and co-occurrence of these deficits results in the most severely impaired reading skills.

Evidence for disrupted letter-speech sound learning in dyslexia mainly comes from brain potential and neuroimaging research demonstrating that in dyslexia, the activity of brain areas involved in the cross-modal integration of letter-speech sound pairs, is reduced in response to letter-speech sound associations (Blomert, 2011; Žarić et al., 2014). Behavioral evidence for deficits in letter-speech sound learning in dyslexia is scarce. A few studies have reported that children with dyslexia have difficulties mastering letter-speech sound correspondences (Blomert & Vaessen 2009; Fox, 1994; Siegel & Faux, 1989; Snowling, 1980), but the actual process of learning these mappings was not directly addressed.

In a previous study (Aravena, Snellings, Tijms, & van der Molen, 2013 -Chapter 3-), we have examined letter-speech sound learning within an artificial orthography. The script was artificial in the sense that unfamiliar letters (Hebrew) were used to transcribe participants' native language (Dutch). This enabled us to compare the initial steps of dyslexic and typical readers in learning a novel script without concerns about possible differences in previous exposure to experimental stimuli. Children were asked to learn eight basic letter-speech sound correspondences within this artificial orthography. After the training, both letter knowledge and word reading ability in the unfamiliar script were assessed. The findings indicated that the basic knowledge of these new correspondences was learned equally well by the children with dyslexia and the typical readers. Importantly, however, typical readers outperformed children with dyslexia when speech sounds had to be matched to their corresponding letters under time pressure. Under these time-restrained conditions children with dyslexia were much more prone to errors than their controls. The results also demonstrated that typical readers read the artificial script considerably faster than the children with dyslexia. Collectively, these findings indicated that the process of learning letter-speech sound correspondences is impaired in dyslexia.

Current study

The aims of the current study were twofold. First, the results from our previous study encouraged us to refine the training, optimizing it for further study and making it suitable for diagnostic assessment of dyslexia. We were specifically interested in the potential of this training to predict individual differences in reading and spelling skill and to differentiate between dyslexic readers and typical readers. Second, we wanted to fit the results obtained using this training into the common framework of dyslexia by examining how letter-speech sound learning relates to PA and RAN and by comparing their contributions to predicting individual differences in reading and spelling ability.

With respect to the first aim, we developed a computerized task that directly measured both accuracy and speed of identification of the learned letter-speech sound correspondences. The inclusion of a speed measure is of interest because the quality of audiovisual integration of letter-speech sound correspondences in the brain is primarily reflected in the time course of the neural activation of the concerning units as well as in the associated response latencies of identification on a behavioral level (Blomert, 2011). We thus created a more sensitive tool that allows for further differentiation even when accuracy performance reaches ceiling levels. Moreover, the learning phase was reduced to 20 minutes. In our previous study (Aravena et al., 2013 -Chapter 3-), training length was 60 minutes but a closer inspection of the data revealed that difficulties in letter-speech sound learning manifest themselves already half way through the training. A pilot study indicated that a training of only 20 minutes provided sufficient exposure to all of the stimuli. Such a short duration also makes the training suitable for clinical application.

Besides the benefit of using an artificial script, which allowed for controlling for differences in prior exposure, another important feature of this training is that it is devoted to learning rather than to the level of skill already obtained. An instrument that captures learning in action can be used to identify factors that interfere with the learning of letter-speech sound correspondences. Moreover, this kind of process-oriented testing is potentially capable of predicting future reading gains in dyslexia intervention (Gustafson, Svensson, & Fälth, 2014).

With respect to the second aim, we capitalized on the available data from the diagnostic assessment and compared the scores from the artificial orthography-related tasks to those from PA and RAN tasks within the group of children with dyslexia. The fact that the training is orthographically unrelated to standard PA and RAN measures, offers a unique opportunity to study the relation between letter-speech sound learning and these traditional measures on a fundamental level, without concerns about reciprocity between literacy and phonological skills. The results thus may shed light on the nature of PA and RAN and on how they are related to reading and spelling skills.

Method

Participants

Our sample consisted of 72 children (42 boys and 30 girls) diagnosed with dyslexia and 46 children (22 boys and 24 girls) with average or above average reading and spelling skills. The age ranged from 7.33 to 11.08 years. All participants were primary education pupils and were native speakers of Dutch.

The children diagnosed with dyslexia were recruited from the IWAL Institute, a nation-wide center for dyslexia in the Netherlands. Selection of the dyslexic group followed standard criteria for severe dyslexia in the Dutch health care system (Blomert, 2006). Children were selected for the study if they met all of the following three inclusion criteria: (1) either word reading speed was 1.5 Standard Deviation (*SD*) or more below average or, word reading speed was at least 1 *SD* below average together with a spelling skill of 1.5 *SD* or more below average; (2) performance on at least two out of six administered phonology-related tasks was at least 1.5 *SD* below average; and (3) the child had shown a poor response to intervention provided at school.

The non-impaired readers were selected from the same sample of schools as the dyslexic readers, to control for SES, demography, and level and amount of education. Allocation to the control group was based on the school record. We selected normal achieving children within general education. Children were only selected when both their reading and spelling grades were above the 25th percentile.

Participant characteristics are shown in Table 1. There were no significant baseline differences between the two groups with respect to age ($p > .05$). We did find a significant baseline difference, however, on the intelligence measure. The dyslexic readers obtained scores close to the general population mean, while the typical readers obtained scores slightly above this mean. This difference may be an artifact of the abovementioned selection criteria for the non-impaired readers. To avoid potential confound, we performed additional analyses after matching the two groups on their scores on a non-verbal reasoning task and an expressive vocabulary task. These analyses indicated that group differences in intelligence did not change the pattern of findings.

Table 1:
Participant characteristics

	Dyslexic (*n*=72)	Control (*n*=46)
	M (SD)	*M (SD)*
Age	9.26 (1.07)	9.37 (0.74)
IQ	5.52 (1.24)	6.38 (1.21)

Exclusion criteria for both groups were uncorrected sensory disabilities, broad neurological deficits, insufficient education, and ADHD. Because we incorporated Hebrew graphemes in our assessment, previous experience with Hebrew script was also an exclusionary criterion. Informed consent was obtained from the parents of each child, and the study was approved by the ethical committee of the university.

Training

Based on the training we used in our previous study (Aravena et al., 2013 -Chapter 3-) we developed a 20 minute letter-speech sound training consisting of a computer game in which the child had to match speech sounds to their corresponding orthographic representations. Correct associations led to success in the game, while incorrect associations jeopardized a positive outcome. Fast playing was reinforced by progressive time restrictions and by providing bonuses for fast playing. More specific, children operated a cannon at the bottom of the screen, moving it horizontally. The upper part of the screen was composed of columns of balloons containing single graphemes. Children were required to act on speech sounds that were presented repeatedly in the game. The response consisted of releasing bullets from the cannon and associating them to their corresponding grapheme. When children managed to clear a field of balloons, a new field was presented. As the amount of distractor graphemes increased during the game, fields became gradually more complex. Figure 1 depicts some screenshots from the game.

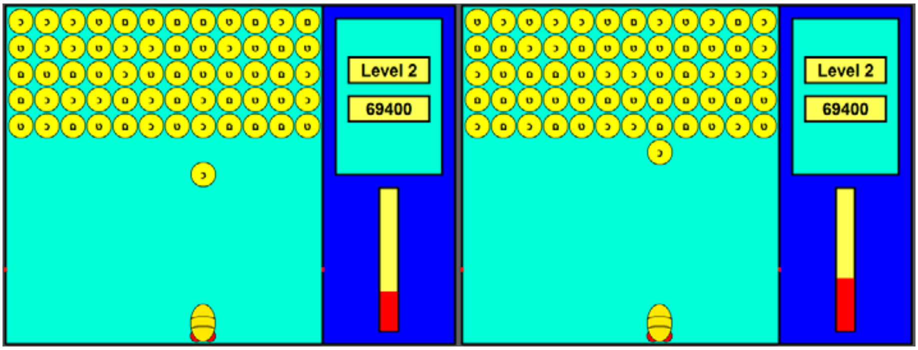


Figure 1 Screenshots from the game

The goal of the training was to learn a set of letter-speech sound correspondences from an artificial orthography. At the start of the game the child was presented with a standardized instruction that was integrated in the software. This instruction clarified the specifics of the game but did not reveal the underlying learning objective. After the instruction, children received a short practice trial to become familiar with the set-up and the controls of the game. During the training session children were wearing headphones.

The artificial orthography consisted of eight Hebrew graphemes, which were randomly matched to Dutch phonemes, thereby providing eight basic non-existing letter-speech sound pairs. The script represents three vowels and five consonants. Combinations of phonemes producing strong co-articulation effects were avoided. Table 2 displays an overview of the letter-speech sound correspondences that were used. The directionality of the script was left-to-right.

Table 2:
Letter-speech sound correspondences within an artificial orthography

Letter	ט	כ	ם	ף	פ	צ	ך	ש
Speech sound (IPA)	[u]	[ɛ]	[ɑ]	[k]	[r]	[l]	[t]	[n]

Note: IPA, International Phonetic Alphabet

Measures

Letter-speech sound identification task within the artificial orthography

In this task, a phoneme was presented over headphones, while simultaneously two graphemes from the artificial orthography were displayed at the screen. One of these graphemes corresponded with the presented phoneme, while the other acted as a distractor. By striking the corresponding button the child had to decide as fast as possible which of the graphemes belonged to the presented phoneme. The task consisted of 56 items. Responses, including latencies, were recorded automatically by the software. Accuracy score was defined as the number of correct responses. The speed score was represented by the median of the response latencies of the correct responses.

Reading task within the artificial orthography

We administered a time-limited test (3MAST, Aravena et al., 2013 -Chapter 3-) consisting of a list of 22 high-frequent Dutch words written within the artificial orthography. The words were presented in lowercase Arial typeface, font size 24, and arranged in two columns of equal length. The child had to read (column-wise) as many words as possible within three minutes. The score was determined by the number of words read correctly per second.

Word reading

We used a time-limited task from the 3DM, a computerized test battery (Blomert & Vaessen, 2009), for assessing word-reading skills in Dutch. This word-reading task included three different levels comprising high-frequency words, low-frequency words and pseudowords. Each level contained 75 words, displayed on 5 sheets with 15 items each. The difficulty of each level increased systematically from monosyllabic words without consonant clusters to 3 or 4 syllabic words with consonant clusters in the fifth sheet. The child was instructed to read accurately as many words as possible within a time-limit of 30 seconds per level. Both accuracy (percentage of correctly read words) and speed (number of words read correctly) were measured (respectively *r* = .73 and *r* = .95, test-retest).

Spelling recognition

Spelling recognition in Dutch was assessed using a computerized task from the 3DM (Blomert & Vaessen, 2009). In this task a word was presented over headphones while it was also visible on the screen. In the visually presented word a letter or letter combination was missing. By striking a key the child had to decide as fast as possible which of four different letters or letter combinations represented the missing part. Both accuracy and response speed were measured (*r* = .80 for accuracy and *r* = .94 for speed, internal consistency).

Spelling-to-dictation

Spelling-to-dictation was assessed using the IWAL Word dictation task (Braams, 1989). This task contained 40 familiar Dutch monosyllabic words, representative of the various spelling problems in Dutch. Scoring was based upon the number of spelling errors (*r* = .89, test-retest).

Phonological awareness

We assessed PA with a phoneme deletion task from the 3DM (Blomert & Vaessen, 2009). In this task the child had to delete consonants from aurally presented pseudowords as fast as possible. The score was determined by the percentage of correct responses. (*r* = .85, internal consistency).

Rapid naming

We assessed both RAN of letters and digits by using a task from the 3DM (Blomert & Vaessen, 2009). The child had to name aloud items presented on the computer screen as fast and accurate as possible. Within both domains, sheets containing 15 items each were presented two times. The score per subtask was determined by taking the mean response speed of the two sheets (*r* = .80 for letters and *r* = .83 for digits, split-half reliability). In the current study we used a composite measure of alphanumeric RAN consisting of the scores of both the RAN of letters and digits.

Intelligence measure

General intelligence was assessed by the subtest Analogies from the SON-R (Laros & Tellegen, 1991), a non-verbal reasoning-by-analogy task in which the child had to extract a principle and apply it to a new situation (r = .79, test-retest), and the subtest Vocabulary from the WISC-III (Kort et al., 2005), a measure of expressive vocabulary requiring the child to describe the meaning of words of increasing complexity (r = .90, test-retest). The score was determined by averaging the standardized C-scores (M = 5, SD = 2) of both tests.

Baseline response speed

We assessed baseline response speed using a task from the 3DM (Blomert & Vaessen, 2009). In this task 4 horizontally arranged squares were presented on the computer screen. Whenever a figure appeared in one of the squares the child had to respond to it, as fast and accurately as possible, by striking the corresponding key. Mean reaction time was computed across 20 items. (r = .93, internal consistency).

Procedure

The session, which had a total duration of approximately one hour, took place on a one-to-one basis and consisted of four steps. First, we provided the 20 minute letter-speech sound training. After the training we administered the letter-speech sound identification task and the reading task within the artificial orthography consecutively. These two tasks took approximately 10 minutes. In the remaining 30 minutes we assessed non-verbal reasoning and expressive vocabulary. The typical readers attended their session at school and the dyslexic readers at the nearest branch of the dyslexia institute. All sessions took place in a silent room. For both the training and the letter-speech sound identification task we used a Lenovo ThinkPad Edge 0319 15,6-inch laptop computer in full screen mode. We derived the scores concerning reading and spelling, PA, RAN, and baseline response speed from the standard diagnostic assessment of the children with dyslexia. The training session and subsequent assessment took place on the same day as this diagnostic assessment.

Results

Differentiating dyslexic and typical readers

In order to examine whether the brief training would differentiate between dyslexic and typical readers we compared both groups on the various artificial orthography-related measures. First, we conducted an independent t-test to determine whether dyslexic readers and controls differed with regard to the identification of letter-speech sound correspondences in the artificial orthography. The mean scores and standard deviations thus obtained are shown in Table 3. The results indicate that, on average, controls were more accurate on the identification task than the dyslexic readers, $t(89{,}773) = -4.496$, $p = .001$, with a medium to large effect size ($r = .43$). Moreover, the controls responded faster on the same test than the dyslexic readers, $t(111{,}648) = 3.397$, $p = .001$, with a medium effect size ($r = .30$).

Table 3:
Means and standard deviations on training-related tasks

	Dyslexic (*n*=72)	Control (*n*=46)
	M (SD)	*M (SD)*
Letter-speech sound identification accuracy	50.08 (6.30)	53.65 (1.90)
Letter-speech sound identification speed	1577.14 (385.37)	1362.30 (298.41)
Number of words read per second	0.0497 (0.0507)	0.0732 (0.0601)

A second analysis focused on the ability to read the novel script following training. Table 3 displays the mean scores and standard deviations. The results from the independent t-test show that the controls read significantly more words per second than the children with dyslexia, $t(115) = -2.279$, $p = .013$, with a modest effect size ($r = .21$).

Predicting group membership

To gain more insight into the extent to which the measures from the brief training are able to correctly predict group membership (dyslexic readers vs. typical readers) we conducted logistic regression analysis and a receiver operator characteristic (ROC) curve analysis (Swets, 1988). The results of these analyses indicate that both the accuracy measure, *Exp(B)* = 1.24, p = .007, and speed measure, *Exp(B)* = 1.00, p = .034 from the identification task, made a significant contribution to predicting group membership. Classification based on these two measures was accurate at 68.6% (see Table 4). As indicated by the area under the ROC curve, AUC = .74, p < .001, the diagnostic accuracy of the identification task can be classified as fair (Youngstrom, 2014).

Tabel 4:
Logistic regression analysis predicting the presence of dyslexia with cutoff value p = .05

	Predicted		
	Dyslexic	Control	Prediction rate
Observed			
Dyslexic	55	17	76,4%
Control	20	26	56,5%
Prediction rate	73,3%	60,5%	

With an overall prediction rate of 62.4%, the number of words read per second also made a significant contribution to predicting group membership, *Exp(B)* = 2332.352, p = .03. The area under the ROC curve, AUC = .65, p = .007, indicated a low to moderate diagnostic accuracy (Youngstrom, 2014), making it less suitable for clinical application. Accordingly, adding this measure to the aforementioned logistic regression model did not significantly improve its ability to correctly predict group membership.

These findings indicate that after only 20 minutes of training the controls outperformed the dyslexic readers in identifying the newly learned letter-speech sound correspondences. Although accuracy was high overall, the dyslexic readers made substantially more errors (11%) than the typical readers (4%). Importantly, these differences in mastery between the groups, expressed in accuracy as well as in speed, also resulted in significant differences in the number of words read per second.

Table 5:
Correlation matrix (semi-partial) *n*=71

	1	2	3	4	5	6	7	8	9	10
1 L-SS Identification accuracy	1									
2 L-SS Identification speed	-.043	1								
3 Words per second (artificial)	.413**	-.377**	1							
4 Phonological awareness	.086	-.150	.293**	1						
5 Rapid naming alphanumeric	-.085	.414**	-.237*	.082	1					
6 Word reading accuracy	.015	.075	.237*	.191	.004	1				
7 Word reading speed	.147	-.214*	.392**	-.071	-.488**	.416**	1			
8 Spelling recognition accuracy	.312*	-.058	.198*	.250*	-.069	.245*	.297*	1		
9 Spelling recognition speed	.057	.334**	-.223*	-.052	.327**	-.128	-.414**	.031	1	
10 Spelling-to-dictation	-.221*	.098	-.407**	-.439**	.007	-.382**	-.402**	-.491**	.147	1

*** significant at the .01 level*

** significant at the .05 level*

Correlation analysis

In order to determine the relation between the measures that were used to tap letter-speech sound learning within the artificial orthography, the traditional phonological measures, and reading and spelling skills, we computed Pearson semi-partial correlations, from which the concomitant effect of age was removed. Note, that, as discussed in the introduction, these analyses were only conducted within the group of dyslexic readers. All correlations are presented in Table 5. The results indicate that the reading task within the artificial orthography correlated significantly with phonological awareness (PA) and rapid automatized naming (RAN). Furthermore, the speed measure of the identification task correlated significantly with RAN. This correlation was still significant after controlling for baseline response speed, $r = .396$, $p = .001$.

We observed that the reading accuracy measure was moderately correlated with the number of words read per second within the artificial orthography, but not with other measures. Reading speed showed a pronounced correlation with both RAN and the number of words read per second within the artificial orthography, and a moderate correlation with the speed measure of the identification task. For the computerized spelling recognition task, accuracy was found to be moderately correlated to PA, accuracy on the identification task, and the number of words read per second within the artificial orthography. Speed of spelling recognition showed a strong correlation with RAN and speed on the identification task, and a moderate correlation with the number of words read per second within the artificial orthography. Furthermore, we found the number of errors on word dictation to be strongly correlated with PA and the number of words read per second within the artificial orthography, and to be moderately correlated to accuracy on the letter-speech sound identification task. All significant correlations were in the expected direction.

Predicting individual differences in reading and spelling skill

We explored the contribution of each of the five variables in predicting individual differences in reading and spelling skills using relative importance weights (RIW) analyses. RIW analysis is an extension of multiple regression that allows for more accurate partitioning of variance and that is particularly suitable for estimating the relative importance of predictor variables that are correlated with one another (Johnson, 2000; Tonidandel & LeBreton, 2011). We adopted this additional procedure, as we were primarily interested in the relative importance of our new predictor variables compared to the well-established traditional predictors and less in their absolute contribution to the coefficient of determination. This was all the more important because the age range of our sample was relatively wide, while the variance of the dependent variables and predictor variables was limited due to the fact that the analyses only referred to the sample of children diagnosed with dyslexia. Moreover, given the intercorrelations between our predictors, beta coefficients might not be the best suited to index relative importance (Kraha, Turner, Nimon, Zientek, & Henson, 2012; O'Neill, McLarnon, Schneider, & Gardner, 2014). RIW improves the interpretation of results of multiple regression within this context by transforming predictor variables into their maximally related orthogonal counterparts and using these transformed variables to predict the criterion (Johnson, 2000).

Table 6:
Regression model predicting reading measures

		Reading Accuracy		Reading Speed	
Steps		R^2	ΔR^2	R^2	ΔR^2
1	age	.19	.19**	.39	.39**
2	PA RAN LSS-A LSS-S WPS	.29	.10	.59	.20**

*Note: PA, phonological awareness, RAN, rapid automatized naming, LSS-A, letter-speech sound identification accuracy, LSS-S, letter-speech sound identification speed, WPS, words per second read in the artificial orthography. ** significant at the .01 level*

Table 6 and 7 display the outcomes of the regression analyses on which the RIW analyses of the current study are based. In each of the analyses, age was entered on the first step, while the five predictor variables—PA, alphanumeric RAN, identification of letter-speech sound correspondences (accuracy and speed), and the number of words read per second within the artificial orthography—were entered as the second step. The results indicate that, in all of the analyses, age accounted for a substantial amount of variance. As aforementioned, this result was expected due to the rather wide age range of our sample and the limited room for variance of the predictor variables within the sample of children diagnosed with dyslexia. More importantly, our results indicated that the predictors of interest made additional contributions in accounting for group differences in reading and spelling skills.

Table 7:
Regression models predicting spelling measures

		Spelling Accuracy		Spelling Speed		Speling-to-dictation	
Steps		R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2
1	age	.36	.36**	.27	.27**	.33	.33**
2	PA RAN LSS-A LSS-S WPS	.47	.11*	.40	.13**	.52	.19**

*Note: PA, phonological awareness, RAN, rapid automatized naming, LSS-A, letter-speech sound identification accuracy, LSS-S, letter-speech sound identification speed, WPS, words per second read in the artificial orthography. ** significant at the .01 level; * significant at the .05 level*

The findings from the RIW analyses, which are presented in Figure 2, shed light on the relative contribution of each of the predictor variables. Note that this figure shows a set of weights that represent each predictor's relative importance to the prediction of the criterion in the context of the total variance accounted for by the set of predictors. To provide insight into the extent to which the RIW analyses had impact on the relative contribution of the predictors, the results from multiple regression analyses are presented in the Appendix to provide a frame of reference. The overall picture of these multiple regression analyses is consistent with the RIW analyses, showing a significant and unique contribution of the artificial orthography-related measures to predicting individual differences in reading and spelling skills.

When it comes to predicting reading accuracy, the number of words read per second within the artificial orthography contributed more than half (53%) to the remainder of the coefficient of determination after age has been accounted for (ΔR^2 step 2). Most of the remaining variance was claimed by PA (24%) and speed on the letter-speech sound identification task (18%). With regard to reading speed, the most important contribution to the ΔR^2 of step 2 came from RAN (54%), followed by the number of words read per second within the artificial orthography (34%).

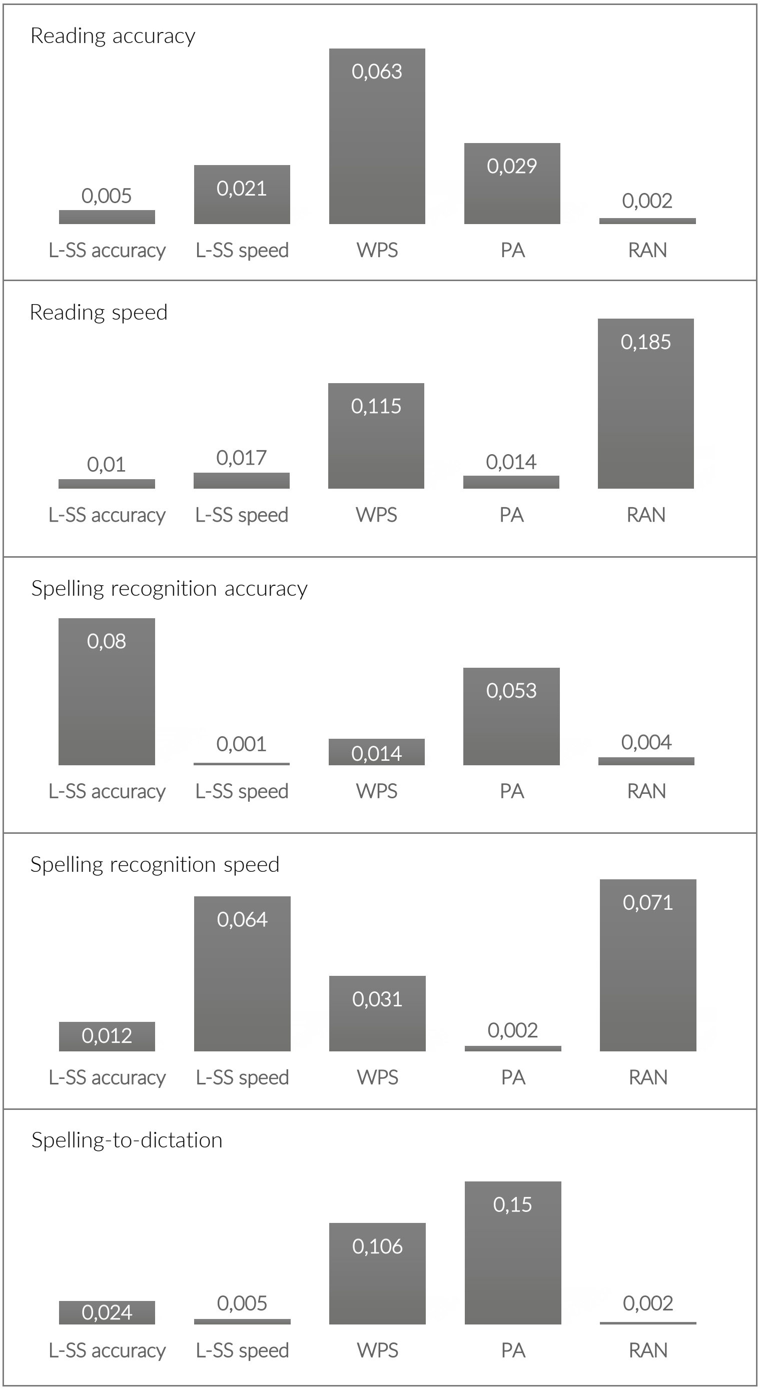


Figure 2 Relative importance weights analyses

For the spelling recognition tasks the accuracy measure was best predicted by accuracy on the letter-speech sound identification tasks (52,6%), followed by PA (35%). We obtained a different pattern of results when decomposing the remainder of the R^2 of the speed measure of the spelling recognition task. Here, RAN (39%) and speed on the letter-speech sound identification task (36%) were responsible for the largest contribution. The number of words read per second within the artificial orthography claimed a modest part of the remainder of the R^2 of both accuracy (9%) and speed (17%) of the spelling recognition task. In predicting the spelling-to-dictation task, PA contributed most to the ΔR^2 of step 2 (52%), followed by the number of words read per second within the artificial orthography (37%).

To sum up, the results demonstrate that a 20-minutes letter-speech sound training within an artificial orthography differentiates between dyslexic and typical readers. The effect of this training is related to PA and RAN and makes a substantial and unique contribution in predicting individual differences in reading and spelling ability when compared to these traditional predictors.

Discussion

In the current study we examined letter-speech sound learning within an artificial script and focused on its potential to differentiate between dyslexic readers and typical readers, its contribution to variance in reading and spelling skills, and its relation to phonological awareness (PA) and rapid automatized naming (RAN). We employed a relatively short training of only 20 minutes aimed at learning eight basic letter-speech sound correspondences within an artificial orthography, followed by a short assessment of both mastery of these correspondences and word reading ability in this unfamiliar script.

Our results indicate that the short training is successful in differentiating dyslexic readers from typical readers in their ability to learn letter-speech sound correspondences. The typical readers outperformed the dyslexic readers on both accuracy and speed on a letter-speech sound identification task and on a word reading task containing familiar words written in the artificial orthography. These results fit well with our earlier finding that dyslexic readers are fundamentally hampered in their ability to learn letter-speech sound correspondences and that the manifestation of this binding deficit can be evoked at any time by presenting them with a novel script (Aravena et al., 2013 -Chapter 3-), giving further support for the notion that a letter-speech sound binding deficit is a key factor in dyslexia (Blomert, 2011; Hahn et al., 2014; Jones et al., 2016; van Atteveldt & Ansari, 2014).

To assess how letter-speech sound learning within an artificial orthography relates to traditional phonological measures, we examined PA and RAN within the group of children with dyslexia and conducted correlational analyses. In line with studies indicating that RAN taps non-phonological cognitive components important to reading (Norton & Wolf, 2012), we did not find a significant correlation between the scores on the phoneme deletion task and the alphanumeric RAN task. However, we did observe RAN to be strongly related to the speed measure of the letter-speech sound identification task within the artificial orthography, which is interesting given the fact that the tasks are orthographically dissimilar. We believe this finding is important, in that it may contribute to the ongoing discussion on the mechanisms that are responsible for the relation between RAN and reading. Possible mediators between RAN and reading that have commonly been put forward in this context are phonological processing, orthographic processing, processing speed, serial processing, and articulation of specific names (Georgiou, Parrila, & Papadopoulos, 2016; Kirby, Georgiou, Martinussen, & Parrila, 2010). Interestingly, none of these factors seems to be a likely candidate for explaining the correlation between RAN and the speed measure of the letter-speech sound identification task within the artificial orthography. The current observation that these measures are orthographically unrelated and that neither is correlated to PA, indicates that the relation must not be sought in phonological or orthographical knowledge. Neither does general processing speed seem to be the underlying factor, as controlling for baseline response speed did not affect the correlation between measures. Lastly, as our letter-speech sound identification task does not appeal to serial processing nor to articulation, it seems that the observed correlation between alphanumeric RAN and speed on the letter-speech sound identification task within the artificial orthography must originate from some other factor; one that also may drive the relationship between RAN and reading. A plausible interpretation would be that speed of letter-speech sound identification provides a potential index of the ability to instrumentally use newly learned letter-speech sound correspondences in reading. Poorly integrated letter-speech sound mappings therefore lead to slow and laborious naming, and, following from this, to poor reading as well. On this account, it is the extent to which letter-speech sound correspondences are automatized that mediates between RAN and reading proficiency. This interpretation is consistent with the view put forward by Bowers and Wolf (1999), who suggested that disturbed naming speed may result in reading failure because of impeded amalgamation of connections between phonemes and orthographic patterns.

We also obtained a correlation between RAN and the number of words read per second in the artificial script. This is not a surprise given the fact that this task also capitalizes on efficient letter-speech sound learning. It was unexpected, however, that the number of words read per second also correlated with PA, while the two measures from the letter-speech sound identification task were found to be unrelated to PA. A possible explanation for this finding is that, although the tasks are orthographically unrelated, they both strongly appeal to decoding skill. From this perspective, the number of words read per second in the artificial script is correlated with RAN because both tasks depend on mastery of letter-speech sound correspondences, and with PA because both tasks require decoding skills.

Considering the correlations between the traditional phonological measures and the new artificial orthography-related measures on the one hand, and the various reading and spelling measures on the other, we see a familiar pattern of results in which PA seems to be more related to accuracy measures of reading and spelling, while RAN is more related to speed measures of reading and spelling. The findings from our artificial orthography-based measures observe this accuracy-speed division, with accuracy on the identification task predicting reading and spelling accuracy measures while speed on the identification task is predicting reading and spelling speed. Intriguingly, the number of words read per second within the artificial orthography correlated significantly with all reading and spelling measures within our study and, thus, does not seem to coincide with the accuracy-speed division. As the number of words read per second within the artificial orthography is correlated with all other measures, it seems that this task shares components with phonology-related skills as well as with both reading and spelling, irrespective of whether accuracy or speed is the focus of attention.

It should be noted that the results from the correlational analysis do not coincide with the findings from the T-test. Based on the high correlation of the number of words read per second with other relevant measures, one would expect it to be the most effective measure to differentiate between the two groups. However, the t-test shows that dyslexic and typical readers seem to differ only moderately on the reading task within the artificial orthography. This unexpected finding might indicate that the artificial reading task is related more strongly to reading in typical readers than the measures from the identification task. Accordingly, the identification task differentiates better between the two groups. This interpretation must remain speculative given the differential amounts of data collected from our dyslectic vs. typically reading participants.

In view of the potential value of the three artificial orthography-related measures for clinical practice, we applied relative weight analyses to examine the relative contribution of these new measures vis-a-vis the traditional combination of PA and RAN. The findings indicated that the new predictors made meaningful and partly independent contributions to explaining individual differences in reading and spelling skills. A combination of conventional testing and these new measures, thus, constitute a stronger predictor of individual differences in reading and spelling skills than conventional testing alone, which stresses the potential benefit of the current learning procedure for the clinical assessment of dyslexia.

The finding that the number of words read per second within the artificial orthography predicts both reading and spelling, as well as both accuracy and speed, raises questions about the nature of this skill. What exactly does it embody? We believe that this skill probably requires the ability to instrumentally use newly learned letter-speech sound correspondences. It is this ability that determines whether someone succeeds in applying the new mappings within a cognitively demanding task, such as reading. By this we do not imply that our task provides a tool to directly assesses the integration of letter-speech sound correspondences. Obviously, such a process needs much more time to be accomplished. But we do believe that it reveals a fundamental underlying problem responsible for the hampered integration of letter-speech sound correspondences. Moreover, in addition to the mastery of letter-speech sound correspondences, fast reading within the artificial orthography also requires decoding skill within a context that does not support fast orthographic pattern recognition, which explains its relation with PA, and makes it a strong predictor of individual differences in reading and spelling skills, both within the domain of accuracy and speed.

Obviously, there are other possible explanations for the fact that the number of words read per second within the artificial orthography predicts different reading and spelling measures. Decoding skill seems to be an important factor related to this task and, besides a letter-speech sound learning deficit, other difficulties may lead to decoding problems. Therefore, we cannot rule out other mediating factors, such as difficulties storing speech sounds in working memory (e.g. Wang, Allen, Lee, & Hsieh, 2015).

An important theoretical question concerns the relation between deficient letter-speech sound learning and the assumed deficit in the phonological processing system. We did not obtain evidence for the view that poor PA results in reading problems because it hinders the establishment of proper letter-speech sound mappings. Letter-speech sound identification within the artificial orthography was not found to be correlated to PA. Moreover, the measures related to the artificial orthography contributed uniquely in accounting for the variance in reading and spelling skills. Given this pattern of results, it seems unlikely that disrupted letter-speech sound learning could be simply explained as a result of poor PA or any other phonological factors. It rather seems that disrupted letter-speech sound learning is at least a partly independent factor underlying dyslexia. This conclusion is in line with findings reported previously by Blomert and Willems (2010) and McNorgan, Randazzo-Wagner, & Booth (2013).

The current procedure is particularly suitable for cross-linguistic comparison of individuals with dyslexia, as it is not restricted to a specific language. This is of considerable interest because the complexity of the particular orthography that an individual has to master has been identified as a central environmental factor associated with dyslexia (Landerl et al., 2013; Seymour, Aro, & Erskine, 2003). Some adjustments to the set of phonemes might be necessary though, because results across languages can only be compared when phonemes are shared or non-existent in each of them. Taking this into account, the current training could be used as a universal measure for assessing the strength of letter-speech sound learning. A similar approach could be adopted for diagnosing dyslexia in a second language.

Standard reading and spelling measures, as well as phonology-related measures, usually fall short because they cannot discard the confounding influence of less language proficiency in the second language. In a recent study Elbro, Daugaard, and Gellert (2012) demonstrated that dynamic assessment of acquiring decoding abilities in an artificial script provides a useful way of circumventing this confounding influence in the context of assessing dyslexia.

An interesting avenue for future research would be to explore letter-speech sound learning in individuals with severe reading and spelling difficulties who do not show a phonological deficit. The fact that not all children with persistent phonological deficits develop reading disabilities and that some children show severe reading disabilities despite normal phonological abilities, has led to the view that, although phonological deficits are standard in dyslexia, multiple factors, including non-phonological factors, interact in a complex way to cause reading impairment (Peterson & Pennington, 2012). An example of a non-phonological factor that has been proposed as an independent cause of reading impairment is poor visual attention (e.g. Bosse, Tainturier, & Valdois, 2007). According to this point of view, reading acquisition is impaired because the quantity of visual information that can be processed at a glance is reduced. It would be of interest to investigate whether children with poor visual attention span, but with intact phonological abilities, also perform poor when adopting the procedure developed in the current study.

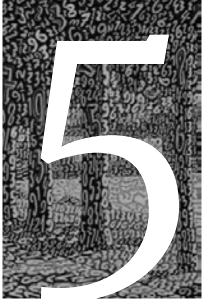
In conclusion, our findings show that a brief training for efficiently learning new letter-speech sound correspondences predicts individual differences in reading and spelling ability and contributes, moderately but significantly, to predicting group membership. It seems that pooling the strengths of conventional testing and the current training procedure could improve the assessment of dyslexia. Particularly, the number of words read per second within the artificial orthography was found to be valuable in this context, as it seems to predict variance within a wide range of reading and spelling skills, both within speed and accuracy domains. Importantly, the training refers to learning artificial letter-speech sound correspondences. This implies that there are no a-priori differences in exposure to the stimuli at the start of the assessment. In this respect, the training would provide a relatively 'pure' assessment compared to traditional instruments, in the sense that typical reciprocity between reading development and phonological development is circumvented. Traditional tests can be used to determine if letter-speech sound correspondences are weak, but they do not tell whether this should be attributed to a predisposition, to reading problems or to differences in exposure. In contrast, the current learning procedure allows for the detection of a fundamental learning deficit for letter-speech sound associations. Finally, it should be stressed that the current training procedure is dynamic. Where traditional diagnostic instruments focus on learning that took place prior to the assessment, the current training is carried out as part of the assessment. This kind of process-oriented testing would be a welcome complement to the diagnosticians' toolbox in the clinical practice of dyslexia. Diagnostic assessment should also focus on learning, as dyslexia is classified in terms of a learning disability. Process-oriented diagnostic tools are potentially capable of predicting future reading gains in dyslexia intervention (Gustafson et al., 2014), which is interesting given the current paucity in our knowledge of factors that predict responsiveness to dyslexia intervention (Frijters, 2011; Hoeft et al., 2011; Tijms, 2011).

Appendix:

Multiple regression analyses predicting reading and spelling measures

	Reading accuracy		Reading speed		Spelling accuracy		Spelling speed		Spelling-to-dictation	
	R^2	R^2change	R^2	R^2change	R^2	R^2change	R^2	R^2change	R^2	R^2change
1 Age	.19	.19**	.39	.39**	.36	.36**	.27	.27**	.33	.33**
2 PA	.21	.03	.39	.00	.44	.08**	.27	.00	.46	.14**
3 RAN	.21	.00	.53	.14**	.44	.01	.35	.08**	.47	.00
4 L-SSa	.21	.00	.54	.00	.47	.03*	.36	.01	.48	.02
5 L-SSs	.23	.01	.54	.00	.47	.00	.39	.03*	.48	.00
6 WPS	.29	.06*	.59	.05**	.47	.00	.40	.01	.52	.04*
2 WPS	.23	.05*	.48	.09**	.38	.02	.31	.04*	.44	.11**
3 PA	.25	.01	.50	.02	.44	.06**	.31	.00	.52	.08**
4 RAN	.25	.00	.59	.09**	.44	.00	.37	.06**	.52	.00
5 L-SSa	.25	.01	.59	.00	.47	.03*	.38	.02	.52	.00
6 L-SSs	.29	.03*	.59	.00	.47	.00	.40	.02	.52	.00
2 L-SSs	.19	.01	.42	.03*	.37	.01	.35	.08**	.33	.01
3 WPS	.26	.07**	.48	.06**	.38	.02	.36	.01	.44	.11**
4 PA	.28	.01	.50	.02	.44	.06**	.36	.00	.52	.08**
5 RAN	.28	.00	.58	.09**	.44	.00	.39	.03*	.52	.00
6 L-SSa	.29	.01	.59	.00	.47	.03*	.40	.01	.52	.00
2 L-SSa	.19	.00	.39	.01	.40	.04*	.27	.00	.36	.03*
3 L-SSs	.19	.01	.42	.03*	.41	.00	.36	.08**	.36	.01
4 WPS	.27	.08**	.48	.06**	.41	.00	.37	.02	.44	.08**
5 PA	.29	.01	.50	.02	.47	.06**	.37	.00	.52	.08**
6 RAN	.29	.00	.59	.09**	.47	.00	.40	.03*	.52	.00
2 RAN	.19	.00	.53	.15**	.36	.00	.35	.08**	.33	.00
3 L-SSa	.19	.00	.54	.00	.40	.04*	.35	.01	.36	.03*
4 L-SSs	.19	.01	.54	.00	.41	.00	.39	.04*	.37	.01
5 WPS	.27	.08**	.58	.05**	.41	.00	.40	.01	.45	.08**
6 PA	.29	.01	.59	.01	.47	.06**	.40	.00	.52	.07**

*Note: PA, phonological awareness, RAN, rapid automatized naming, LSS-A, letter-speech sound identification accuracy, LSS-S, letter-speech sound identification speed, WPS, words per second read in the artificial orthography. ** significant at the .01 level; * significant at the .05 level*



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CHAPTER

Predicting responsiveness to intervention in dyslexia using dynamic assessment

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Abstract

In the current study we examined the value of a dynamic test for predicting responsiveness to reading intervention for children diagnosed with dyslexia. The test consisted of a 20-minute training aimed at learning eight basic letter–speech sound correspondences within an artificial orthography, followed by a short assessment of both mastery of these correspondences and word reading ability in this unfamiliar script. Fifty-five 7- to 11-year-old children diagnosed with dyslexia engaged in specialized intervention during approximately 10 months and their reading and spelling abilities were assessed before and after. Our results indicated that the dynamic test predicted variance in reading skills at posttest, over and above traditional static measures, such as phonological awareness and rapid naming. These findings indicate that responsiveness to learning new letter–speech sound correspondences has a prognostic value for the success of specialized reading intervention.

Introduction

Developmental dyslexia, henceforth referred to as dyslexia, is characterized by a specific and significant impairment in the automatic recognition of written words (Fletcher & Lyon, 2008; Peterson & Pennington, 2012; Snowling, 2012). There is ample evidence that specialized intervention is effective in ameliorating reading and spelling proficiency of children with dyslexia (see Galuschka, Ise, Krick, & Schulte-Körne, 2014 for an overview). Unfortunately, not all dyslexic readers benefit to the same extent and there is a substantial amount of non-responders as well (Galuschka et al., 2014; Singleton, 2009; Torgesen, 2005). Gaining more insight into factors that can predict responsiveness to intervention in dyslexia would be very welcome as it could help us identify non-responders at an early stage and, by doing so, prevent wasting time, effort, and resources on interventions that are not effective.

A framework that is particularly important in this context is response to intervention (RTI), which nowadays is common practice in educational settings across the United States and several European countries. RTI is an approach in which a tutor provides a pupil with progressively intense and individualized tiers of instruction with the aim of finding the best possible way to educate children and of identifying children with learning disabilities (Fuchs & Fuchs, 2006; Grigorenko, 2009; Gustafson, Svensson, & Fälth, 2014). Pupils who do not respond to Tier 1 receive more intensive and individualized instruction within Tier 2, and those who are unresponsive to Tier 2 proceed with even more rigorous instruction within Tier 3. Depending on the educational system, the framework is sometimes complemented by a fourth tier, which consists of placement in special education or referral to assessment and therapy within the health care system.

Although many pupils benefit from RTI as they receive high-quality instruction as soon as learning difficulties arise, the notion that intervention should initially be of modest intensity has been questioned (Denton et al., 2011; Vaughn, Denton, & Fletcher, 2010). Especially the value of Tier 2 intervention for the most learning disabled continues to be a subject to debate (Compton et al., 2012; Fuchs, Fuchs, & Compton, 2010). Indeed, there is evidence that engaging in less intensive tiers of intervention may not be effective for addressing the reading difficulties of children with dyslexia (Vaughn et al., 2010). Early identification of non-responders could thus potentially improve their chance to benefit from intervention by intensifying initial intervention.

A convenient starting point for identifying factors predicting intervention success would be to focus on the standard assessment of dyslexia, which typically consists of a combination of reading and spelling tasks along with a set of phonology-related tasks, such as phonological awareness, rapid naming, and verbal short-term memory, as well as some general cognitive measures. Indeed, several studies indicate that some of these factors, among which poor phonological awareness in particular, can predict unresponsiveness to early literacy intervention within children at risk for dyslexia (see Al Otaiba & Fuchs, 2002 and Nelson, Benner, & Gonzalez, 2003 for an overview), but it is far less clear whether these findings hold for children diagnosed with dyslexia (Frijters et al, 2011; Hatcher & Hulme, 1999; Morris et al., 2012; Tijms, 2011). For this group there is a paucity in our knowledge of factors moderating responsiveness to intervention (Démonet, Taylor, & Chaix, 2004; Frijters et al., 2011; Hoeft et al., 2011; Shaywitz, Morris, & Shaywitz, 2008; Tijms, 2011). A recent meta-analysis including twenty-two randomized controlled trial studies of reading disabled children failed to identify subject-related moderators of responsiveness to intervention (Galuschka et al., 2014).

Dynamic assessment (DA) might be a viable approach for examining potential moderators of responsiveness to intervention. The focus of DA is on learning potential rather than learning outcome (Grigorenko, 2009; Gustafson et al., 2014). A typical DA procedure requires the pupil to engage in a training in which feedback is provided. The effect of training is then used to estimate the pupils' learning potential. There is ample evidence that this kind of process-oriented testing better predicts future learning than conventional testing within various academic domains, including reading skill (Caffrey, Fuchs, & Fuchs, 2008; Fuchs, Compton, Fuchs, Bouton, & Caffrey, 2011; Grigorenko & Sternberg, 1998; Gustafson et al., 2014; Jeltova et al., 2007; Spector, 1992). However, other studies have shown little advantage of dynamic testing over static testing (Caffrey, Fuchs, & Fuchs, 2008). In a recent study Petersen, Allen, and Spencer (2014) compared the utility in predicting reading difficulty at first grade of two DA reading measures and two commonly used one-point-in-time pre-reading measures administered to 600 kindergarten children and found both DA measures to be superior to the common static measures. Recently, DA has also been used to examine moderators of responsiveness to intervention. Cho, Compton, Fuchs, Fuchs, and Bouton (2014) showed that DA predicted the responsiveness to a validated reading intervention program. In this study, first-grade students received Tier 2 reading intervention within small groups during 14 weeks. DA of decoding was found to be a significant predictor of the growth in word identification fluency and the final level attained.

In the current study, we applied DA to children diagnosed with dyslexia in order to predict the success of subsequent specialized Tier 4 intervention. The DA we developed consists of a 20-minute training aimed at learning eight new basic letter–speech sound correspondences, followed by a short assessment of both mastery of the correspondences and word reading ability in this unfamiliar script. Letter–speech sound learning is the central focus of the training, because recent research suggests that a fundamental letter–speech sound learning deficit is a key factor in dyslexia (Blomert, 2011; Kronschnabel, Brem, Maurer, & Brandeis, 2014; McNorgan, Randazzo-Wagner, & Booth, 2013; Mittag, Thesleff, Laasonen, & Kujala, 2013; Peterson & Pennington, 2015; van Atteveldt & Ansari, 2014; Žarić et al., 2014). The advantage of adopting an artificial script is that differences in previous exposure to experimental stimuli can be ruled out, allaying concerns about noncontrolled factors influencing performance. In a previous study we demonstrated that our DA procedure differentiates between dyslexic readers and typical readers and predicts individual differences in reading and spelling ability (Aravena, Tijms, Snellings, & van der Molen, 2015 -Chapter 4-). In the current study we examined whether, in addition to its diagnostic value, the DA procedure has prognostic value as well. The participating children engaged in specialized Tier 4 intervention during approximately 10 months. We tested their reading and spelling abilities before and after intervention and related these to the scores on our DA, as well as to the scores on two conventional static measures frequently used for the assessment of dyslexia, namely a phonological awareness task and an alphanumeric rapid naming task. Unlike most approaches to DA (Grigorenko, 2009; Grigorenko & Sternberg, 1998), our assessment did not involve instruction but just associative learning from exposure and implicit feedback. The 20-minute training consisted of a computer game in which children had to match speech sounds to unfamiliar letters. As correct responses led to success in the game and incorrect responses were penalized, children learned the letter–speech sound correspondences just by playing the game, without being aware of learning. Instructions were only related to the specifics of the game and did not reveal the underlying learning objective. This approach was chosen to approximate letter–speech sound learning as it naturally occurs and to measure the capacity to master new letter–speech sound correspondences, without interference from more general factors related to instruction, such as intelligence, verbal comprehension, or attention.

In brief, in the current study we examined whether a new DA procedure predicted the success of subsequent specialized intervention within a group of children diagnosed with dyslexia. We expected this procedure to be an adequate candidate for this purpose for two reasons. First, because it focuses on the formation of letter–speech sound correspondences, a process that appears to be disrupted in children with dyslexia. Second, because it focuses on learning rate rather than on learning outcome.

Method

Participants

Participants were 55 primary education pupils (30 boys and 25 girls) diagnosed with dyslexia recruited from a nation-wide center for dyslexia in the Netherlands. The children had a mean age of 9 years and 3 months (*SD* = 12.39 months, age range = 7.33–11.08 years). An estimate of general intelligence was obtained by averaging the standardized C-scores (*M* = 5, *SD* = 2) of the subtest Analogies from the SON-R (Laros & Tellegen, 1991), a non-verbal reasoning-by-analogy task in which the child had to extract a principle and to apply it to a new situation (*r* = .79, test–retest), and the subtest Vocabulary from the WISC-III (Kort et al., 2005), a measure of expressive vocabulary requiring the child to describe the meaning of words of increasing complexity (*r* = .90, test–retest). The IQ estimates ranged from 3 to 8.5 (*M* = 5.57, *SD* = 1.37). Informed consent was obtained from the parents of each child.

Consistent with standard norms for severe dyslexia in the Dutch health care system (Blomert, 2006), children were diagnosed with dyslexia when they met all of the following three inclusion criteria: (1) either word reading speed was 1.5 standard deviation (*SD*) or more below average or, word reading speed was at least 1 *SD* below average together with a spelling skill of 1.5 *SD* or more below average; (2) performance on at least two out of six administered phonology-related tasks was at least 1.5 *SD* below average; and (3) the child had shown a poor response to intervention provided at school. Exclusionary criteria were uncorrected sensory disabilities, broad neurological deficits, low IQ (< 80), poor school attendance, and ADHD. Because we incorporated Hebrew graphemes in our assessment, previous experience with Hebrew script was also an exclusionary criterion. All participants were native speakers of Dutch. The study was approved by the University's Ethics Committee.

Dynamic assessment

The dynamic assessment (DA), which had a total duration of approximately 30 min, consisted of a 20-minute training dedicated to learning non-existent letter–speech sound correspondences followed by a short assessment of both mastery of the newly learned correspondences and word reading ability in the artificial script. A summary of the different components of the DA is provided below.

The letter–speech sound training

The training consisted of a computer game in which the child had to match speech sounds to their corresponding orthographic representations (Aravena et al., 2015 -Chapter 4-). Correct associations were rewarded while incorrect associations were penalized. Fast playing was reinforced by progressive time restrictions and by providing bonuses for fast playing. More specific, children operated a cannon at the bottom of the screen, moving it horizontally. The upper part of the screen was composed of columns of balloons containing single graphemes. Children were required to act on speech sounds that were presented repeatedly in the game. The response consisted of releasing bullets from the cannon and associating them to their corresponding grapheme. When children managed to clear a field of balloons, a new field was presented. As the amount of distractor graphemes increased during the game, fields became gradually more complex. Figure 1 depicts some screenshots from the game.

The goal of the training was to learn a set of letter–speech sound correspondences from an artificial orthography. At the start of the game the child was presented with a standardized instruction that was integrated in the software. This instruction provided information regarding the specifics of the game but did not reveal the underlying learning objective. After the instruction, children received a short practice trial to become familiar with the set-up and the controls of the game. During the training session children were wearing headphones.

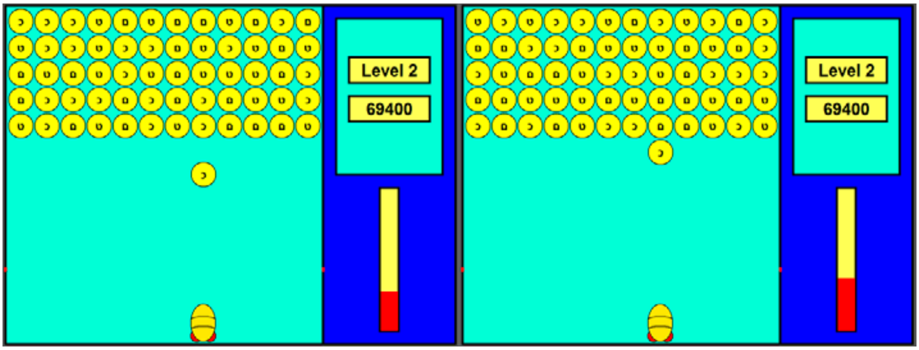


Figure 1 Screenshots from the game

The artificial orthography

The artificial orthography consisted of eight Hebrew graphemes, which were randomly matched to highly frequent Dutch phonemes, thereby providing eight basic non-existing letter–speech sound pairs. Table 1 presents the letter–speech sound correspondences that were used.

Table 1:
Letter-speech sound correspondences within an artificial orthography

Letter	ט	כ	ם	ף	פ	צ	ך	ש
Speech sound (IPA)	[u]	[ɛ]	[ɑ]	[k]	[r]	[l]	[t]	[n]

Note: IPA, International Phonetic Alphabet

We adopted Hebrew script to capture the characteristics of graphemes as they naturally occur. Evidence exists that letter shapes are not an arbitrary cultural choice but rather a product of our neural architecture (Dehaene, 2009, p. 173). The phonemes, three vowels and five consonants, were selected based on their high frequency and their ability to, by combining, create a large corpus of words. Combinations of phonemes producing strong coarticulation effects were avoided. The directionality of the script was left-to-right.

Letter–speech sound identification task within the artificial orthography

In this task a phoneme was presented over headphones, while simultaneously two graphemes from the artificial orthography were displayed on the screen. One of these graphemes corresponded with the presented phoneme, while the other was as a distractor. By striking the corresponding button the child had to decide, as fast as possible, which of the graphemes belonged to the presented phoneme. The task consisted of 56 items. Response speed and accuracy were recorded automatically by the software. The score for response speed was the median speed of correct responses and the score for accuracy was the number of correct responses (respectively $r = .96$ and $r = .90$, split-half).

Reading task within the artificial orthography

We administered a time-limited test (3MAST) consisting of a list of 22 high-frequent Dutch words written within the artificial orthography. The words were presented in lowercase Arial typeface, font size 24, and arranged in two columns of equal length. The child had to read (column-wise) as many words as possible within 3 min. The score consisted of the number of words read correctly per second.

Traditional measures used for the assessment of dyslexia

Phonological awareness

We assessed phonological awareness with a phoneme deletion task from the 3DM, a standardized and computerized battery for assessing dyslexia (Blomert & Vaessen, 2009). In this task the child had to delete consonants from aurally presented pseudowords (CVC or CCVCC structure) as fast as possible (for example /FOT/ minus

/F/ makes /OT/). The score consisted of the percentage of correct responses (*r* = .85, internal consistency).

Rapid naming

We assessed both rapid naming of letters and digits with a rapid naming task from the 3DM (Blomert & Vaessen, 2009). The child had to name aloud items presented on the computer screen as fast and accurate as possible. Within both domains sheets containing 15 items each were presented two times. The score per subtask was the mean response time of the two sheets (*r* = .80 for letters and *r* = .83 for digits, split-half reliability). In the current study we used a composite measure of alphanumeric rapid naming consisting of the scores of both the rapid naming of letters and digits.

Reading and spelling measures

Word reading

We assessed word reading with a time-limited task from the 3DM (Blomert & Vaessen, 2009). This word-reading task included three different levels comprising high-frequency words, low-frequency words and pseudowords. Each level contained 75 words, displayed on 5 sheets with 15 items each. The difficulty of each level increased systematically from monosyllabic words without consonant clusters to 3 or 4 syllabic words with consonant clusters in the fifth sheet. The child was instructed to read as many words as possible while maintaining accuracy within a time-limit of 30 s per level. Both accuracy (percentage of correctly read words) and speed (number of words read correctly) were measured (respectively *r* = .73 and *r* = .95, test–retest).

Spelling

We assessed spelling with a task from the 3DM (Blomert & Vaessen, 2009). In this task a word was presented over headphones while it was also visible on the screen. In the visually presented word a letter or letter combination was missing. By striking a key the child had to decide as fast as possible which of four different letters or letter combinations represented the missing part. Word frequencies varied systematically and words were either phonetically transparent (18 items) or needed the application of a Dutch spelling rule (36 items). Scores consisted of the percentage of accurate responses (*r* = .80, internal consistency).

Specialized intervention

The Dutch educational system utilizes a three-tier approach to reading instruction. Children who do not respond to intensive Tier 3 intervention are assessed for their reading deficiency and those diagnosed with dyslexia receive specialized intervention within the health care system, which in the Netherlands represents the fourth tier. The intervention used in this study was a Dutch computer-based Tier 4 intervention program for treating dyslexia (LEXY).

Intervention was provided by speech therapists and psychologists, on a one-to-one basis in weekly 45-min sessions. Sessions took place in a dyslexia center in the child's neighborhood. Besides these sessions at the center, participants were required to practice at home three times a week for 15 min.

LEXY provides insight into the way written language transcribes the characteristics of the spoken language system by clarifying the phonological and morphological structure, and by explicitly training the rule-systems that are essential for the graphic representation of spoken language, using step-by-step algorithmic plans. All elements within the learning environment (like phonemic and orthographic units and mapping operations) are graphically represented on the computer screen (see Tijms & Hoeks, 2005 for a more detailed review of LEXY). The LEXY program aims at achieving a mastery level for each element of the program, which implies that participants do not pass through it at a fixed pace. On average the duration of the intervention program is 48 to 60 sessions, but in the current study the posttest was administered before the end of intervention, at 39 weeks. The program is in line with guidelines regarding effective intervention for children with dyslexia (Galuschka et al., 2014; Singleton, 2009) and its efficacy has been demonstrated repeatedly (Tijms, 2011; Tijms & Hoeks, 2005).

Design and procedure

The DA was administered as part of a standard diagnostic assessment consisting of two 3.5 hour-sessions within one week interval. A trained psychologist administered the DA on a one-to-one basis during the second session. The assessment took place in a silent room in the dyslexia center. Children started with the intervention program approximately four months after the assessment. The pretest consisted of the word reading and the spelling task and took place during the first session of the intervention. The posttest, which included the same tasks, took place during the 39th session, which was after approximately 10 months (*M* = 43.0 weeks, *SD* = 1.9 weeks), depending on the amount of cancelled sessions due to illness or holidays. In total, 33 sessions were used for intervention and 6 sessions were used for assessment purposes.

Analyses

In order to understand the predictive potential of the pertinent variables, we first had a look at the overall effect of the intervention. Gain values were calculated by subtracting the standardized T-scores (*M* = 50, *SD* = 10) obtained at pretest from those obtained at posttest for each individual. A one-sample t-test was then conducted to determine whether the mean of these gain values was significantly different from zero.

To determine whether the three dynamic assessment (DA) variables predict the improvement in reading and spelling skills during intervention we conducted a series of two-step fixed-entry multiple regression analyses with the posttest scores of reading and spelling measures as the dependent variables. In each of the analyses we entered the pretest score in the first step to filter out variance due to differences at the start of intervention. The three DA measures as well as phonological awareness (PA) and alphanumeric rapid naming (RAN) were added alternately in the second step to determine their individual contribution. In an additional series of multiple regression analyses we compared the predictive potential of the combined DA measures to the combined traditional measures by entering both phonological awareness and rapid naming in the second step and the three DA measures in the third step and vice versa.

Results

Overall effect of the intervention

Table 2 presents the standardized T-scores for the reading and spelling tasks at pretest and posttest. A one-sample t-test showed that the treatment had a significant beneficial effect on reading accuracy ($t(52) = 3.032$, $p = .004$, $d = 0.84$) and on reading speed ($t(52) = 7.071$, $p < .001$, $d = 1.96$) as well as on spelling ($t(52) = 5.937$, $p < .001$, $d = 1.65$). Note that the gains are expressed in standardized scores, and thus reflect a shift in position within the normal distribution. In other words, the reading disabled children that received intervention made significantly more progress than their peers (from the national norm) during the same period.

Table 2:
The development of standardized T-scores for reading and spelling during intervention

	T-score at pretest	T-score at posttest	Gain values (T-score)
	M (SD)	*M (SD)*	*M (SD)*
Reading accuracy	32.44 (11.37)	37.25 (11.64)	5.11 (12.28)**
Reading speed	29.60 (5.09)	34.94 (7.39)	5.45 (5.61)**
Spelling	37.07 (7.28)	44.49 (8.69)	7.75 (9.51)**

*** significant at the .01 level*

Despite the improvements that were made, the average accuracy and speed scores of reading were still below the normal range after 39 sessions of treatment. This was not surprising, however, given that the posttest was administered mid-term. The improvements found at the end of this treatment are typically more substantial (Tijms, 2011; Tijms & Hoeks, 2005).

Predicting reading and spelling gains during intervention

The results from the multiple regression analyses, presented in Table 3, indicate that neither PA nor RAN made a significant contribution to predicting the improvement in any of the reading and spelling skills during intervention. The same was true for the artificial orthography-related accuracy measure of the letter–speech sound identification task (LSSa). The speed measure of the letter–speech sound identification task (LSSs), however, accounted for 17% of the variance in reading accuracy and 6% of the variance in reading speed at posttest. The contribution to the variance in spelling at posttest was negligible. The amount of words read per second within the artificial orthography (WPS) accounted for 12% of variance in reading accuracy at posttest, but did not contribute to the variance of any of the other measures.

Table 3:
Regression models predicting reading and spelling measures at posttest

		Reading Accuracy		*Reading Speed*		*Spelling*	
Steps		*R^2*	*ΔR^2*	*R^2*	*ΔR^2*	*R^2*	*ΔR^2*
1	pretest	.19	.19**	.42	.42**	.09	.09*
2	PA	.21	.02	.43	.01	.09	.00
2	RAN	.21	.02	.42	.00	.09	.00
2	LSSa	.19	.00	.42	.00	.10	.01
2	LSSs	.36	.17**	.48	.06*	.10	.01
2	WPS	.31	.12**	.43	.01	.10	.01

*Note: PA, phonological awareness, RAN, rapid automatized naming, LSS-A, letter-speech sound identification accuracy, LSS-S, letter-speech sound identification speed, WPS, words per second read in the artificial orthography. ** significant at the .01 level; * significant at the .05 level*

Table 4:
Regression models predicting reading and spelling measures at posttest (combined measures)

		Reading Accuracy		Reading Speed		Spelling	
Steps		*R2*	*ΔR2*	*R2*	*ΔR2*	*R2*	*ΔR2*
1	pretest	.19	.19**	.42	.42**	.09	.09*
2	PA						
	RAN	.23	.04	.43	.01	.09	.00
3	LSSa						
	LSSs						
	WPS	.42	.19**	.50	.07	.11	.02
2	LSSa						
	LSSs						
	WPS	.41	.23**	.48	.06	.11	.02
3	PA						
	RAN	.42	.00	.50	.02	.11	.00

*Note: PA, phonological awareness, RAN, rapid automatized naming, LSS-A, letter-speech sound identification accuracy, LSS-S, letter-speech sound identification speed, WPS, words per second read in the artificial orthography. ** significant at the .01 level; * significant at the .05 level*

The results from the additional analyses, which are shown in Table 4, indicate that the three DA measures combined accounted for 23% of variance in reading accuracy at posttest when entered in the second step and for 19% of additional variance when entered in the third step. The three DA measures thus predicted variance in reading accuracy at posttest, over and above traditional static measures, such as PA and RAN.

Discussion

In the current study we used dynamic assessment (DA) for children diagnosed with dyslexia to examine whether it would predict the success of a subsequent specialized intervention. In a previous study we demonstrated that our DA predicts individual differences in reading and spelling ability and differentiates between dyslexic readers and typical readers (Aravena et al., 2015 -Chapter 4-). The results from the current study indicate that in addition to its diagnostic value our DA has prognostic value as well. More specifically we found that the speed measure from the letter–speech sound identification task (LSSs) made a significant contribution to explaining variance in response to intervention on reading accuracy and speed and that the amount of words read per second within the artificial orthography (WPS) accounted for another significant portion of variance in reading accuracy at posttest.

Our findings are consistent with previous findings demonstrating the added value of DA in forecasting reading development (Caffrey et al., 2008; Fuchs et al., 2011; Grigorenko & Sternberg, 1998; Gustafson et al., 2014; Jeltova et al., 2007; Petersen et al., 2014; Spector, 1992) and, more importantly, in predicting responsiveness to reading intervention (Cho et al., 2014). The current study strengthens and extends available data by showing that DA has the potential to predict responsiveness to intervention beyond Tier 3 intervention within a sample of children diagnosed with dyslexia. This is of particular interest because so far the quest for predictors of responsiveness to intervention for this group has not been very fruitful (Frijters et al., 2011; Hoeft et al., 2011; Tijms, 2011). Our results indicate that a dynamic approach to assessment provides new opportunities to predict responsiveness to intervention even for the most reading disabled. From a clinical point of view early identification of potential non-responders is valuable because it may assist practitioners adapting their educational strategies at an initial stage or even start off a prompt deployment of alternative ways of accessing written information, such as computer-based reading.

A possible explanation for the current success of our DA approach is that it not only identifies an essential underlying factor, namely a letter–speech sound binding deficit, but that it also provides an index of the extent to which this underlying problem interferes with learning to read. This explanation is in line with findings from longitudinal studies indicating that deficits in the initial learning of letter–speech sound associations are an important risk factor for developing reading difficulties (Caravolas et al., 2012; Lyytinen, Ronimus, Alanko, Poikkeus, & Taanila, 2007). According to Lyytinen et al. (2007) it is a serious reason for concern when a child struggles storing grapheme–phoneme connections in memory in stable form. We think it is this ‘struggle’ that manifests itself within the 20 min of playing the DA game and, thus, it might provide a proxy for the responsiveness to reading intervention.

It is noteworthy that we did not find any moderating effect of phonological awareness or rapid naming on the responsiveness to intervention. Research has consistently demonstrated that these factors are important predictors of variance in reading skills (see Melby-Lervåg, Lyster, & Hulme and Norton & Wolf, 2012 for reviews). Moreover, some studies did obtain evidence to suggest that these factors can predict responsiveness in children at risk for dyslexia (see Al Otaiba & Fuchs, 2002 and Nelson, Benner, & Gonzalez, 2003 for reviews). The current lack of an association between phonological awareness and rapid naming and response to intervention is in line with the notion that phonological factors may be less important than is often assumed (Byrne, 2011). Observations that, although phonological deficits are common in individuals with dyslexia, a single phonological deficit is not necessary or sufficient to cause the disorder, have led to the idea that poor phonological awareness and rapid naming are two of multiple factors that interact in causing dyslexia (Pennington, 2006; Peterson & Pennington, 2012; Snowling, 2008; Moll, Loff, & Snowling, 2013).

Although the current study did not focus on the effectivity of the intervention per se, but rather aimed at gaining insight into factors that can predict responsiveness to intervention, the intervention gains were derived from national normative data rather than from a direct comparison with a control group within a randomized control trial (RCT) design. Our study thus indicates that the DA procedure is able to predict changes between pretest and posttest, but cannot establish whether these changes result from the intervention. However, it is important to add that findings from a recent RCT-study on the effectiveness of the LEXY program demonstrated that children with dyslexia showed substantial reading and spelling gains after the intervention and improved at a faster rate than both typical readers and waiting-list controls (Fraga González et al., 2015).

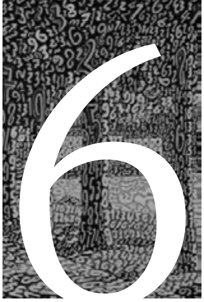
Although our findings indicate that our DA is able to significantly predict progress in reading and spelling skills during specialized intervention, with up to 19% of uniquely explained variance, its predictive power is modest from a clinical perspective. It should be noted, however, that, as we focused on Tier 4 intervention, all children within our sample were characterized by severe and persistent reading and spelling disabilities, limiting variability. Based on the results from other studies (for example Cho et al., 2014 and Petersen et al., 2014) it seems plausible that the predictive potential of the DA will increase when applied to Tier 3 or even Tier 2 intervention.

The findings of the current study raise a number of interesting questions. First, why is LSSs the best predictor among the three DA variables? One possible explanation is that, while LSSa is related to the understanding of the newly learned letter–speech sound correspondences, LSSs, in addition, provides an index of the ability to instrumentally use these correspondences. This interpretation is in line with the literature on dysfunctional letter–speech sound learning, suggesting that the amount of automation of the concerning units at a neuronal level and in identification latencies at a behavioral level, reflects the extent to which the quality of the learned association enables fluent reading (Aravena et al., 2015 -Chapter 4-; Blomert, 2011; van Atteveldt & Ansari, 2014; Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012). Within this context, LSSs seems to be the purest measure of one's ability to automate the learned associations and it is this ability that may to a large extent determine one's responsiveness to intervention.

A second interesting question is why progress in reading speed seems much more difficult to predict than progress in reading accuracy. A possible explanation centers on the duration of the intervention. The literature on skill acquisition clearly indicates that speeding up cognitive processes by obtaining automaticity requires extended amounts of training (Schneider & Chein, 2003; Siegel, 2005). Accordingly, several studies related to specialized reading intervention indicate that gains in reading accuracy largely precede gains in reading rate (Tijms, 2007; Žarić et al., 2014). It is therefore possible that the intervention in the current study is too short to exert a substantial influence on reading rate and that the variance in reading rate at posttest is only minimally related to disrupted letter–speech sound learning. This interpretation is supported by the fact that a substantial part of variance in reading rate at posttest is explained by variance at pretest, which is not the case for reading accuracy.

From a practical perspective it is interesting to reflect on our results in the context of response to intervention (RTI). There is a general concern that many children receive instruction within less intensive tiers only to show their failure in order to gain access to more appropriate instruction (Caffrey et al., 2008; Fuchs et al., 2011; Gustafson et al., 2014; Vaughn et al., 2010). It has been proposed to integrate DA within a RTI framework to overcome the apparent limitations of RTI (Compton et al., 2010; Gustafson et al., 2014; Kantor, Wagner, Torgesen, & Rashotte, 2011; Lidz & Peña, 2009). Compton et al. (2010), for example, reported that the addition of a decoding DA procedure to a base 1st-grade screening significantly improved classification accuracy of children at risk for future reading difficulty within a RTI framework. Additionally, Gellert and Elbro (2015) demonstrated that language-neutral dynamic testing before the onset of reading instruction can predict reading difficulties at the end of Grade 1. The current result that DA predicts the response to intervention before the actual intervention commences adds to these findings and supports the utility of DA in RTI decision-making. It allows for skipping tiers of less intensive intervention or even for starting specialized intervention right away. Importantly, as the current DA procedure can be administered fully automatized with the aid of a computer, it is suitable for large scale implementation.

In conclusion, our findings demonstrate that a short DA procedure based on letter–speech sound learning has a predictive value in assessing a child's susceptibility to long-term intervention. In this regard, the DA procedure may provide a useful tool in the assessment of dyslexia and may qualify as an alternative or supplement to RTI in future research and policy-making. From a theoretical perspective, our findings support the notion that a letter–speech sound learning deficit is a crucial factor within the etiological framework of dyslexia (Blomert, 2011; Kronschnabel et al., 2014; McNorgan et al., 2013; Mittag et al., 2013; van Atteveldt & Ansari, 2014; Žarić et al., 2014).



6
CHAPTER

Caught in the act: Letter-speech sound learning in kindergarten children

Aravena, S., Tijms, J., Snellings, P., & van der Molen, M. W. (submitted). Caught in the act: Letter-speech sound learning in kindergarten children. *Learning and Individual Differences*.

Abstract

In this study we examined letter-speech sound learning within an artificial script in children at familial risk of dyslexia (n=28) and their typical-risk peers (n=28). At the end of kindergarten (T1) we administered a dynamic assessment (DA) consisting of a short computer game in which children were exposed to eight basic letter-speech sound correspondences within an artificial orthography, followed by a short assessment of the mastery of these correspondences. Word reading fluency was assessed two years later at the end of Grade 2 (T2). Our results indicated that 1) the at-risk children (n=22) performed less well on the DA than their typical-risk peers (n=23); and 2) the DA, administered at T1, predicted word reading fluency at T2 over and above traditional measures of letter knowledge and phonological awareness. These findings provided evidence that a letter-speech sound learning deficit is a key factor in dyslexia. Furthermore, our DA was demonstrated to improve the early detection of children at risk for reading disabilities, allowing practitioners to timely adapt their educational strategies to prevent reading disabilities or significantly reduce their impact.

Introduction

In alphabetic languages, learning to associate speech-sounds with unfamiliar characters is a critical step in becoming a proficient reader (Ehri, 2005). Learning these mappings starts off a process that slowly prepares the brain for fluent reading. There is growing evidence that a fundamental impairment in the ability to acquire well-formed associations between speech sounds and the symbols we use to represent them is a key factor in developmental dyslexia, henceforth referred to as dyslexia (Aravena, Snellings, Tijms, & van der Molen, 2013 -Chapter 3-; Blomert, 2011; Kronschnabel, Brem, Maurer, & Brandeis, 2014; McNorgan, Randazzo-Wagner, & Booth, 2013; Mittag, Thesleff, Laasonen, & Kujala, 2013; Moll, Hasko, Groth, Bartling, & Schulte-Körne, 2016; van Atteveldt & Ansari, 2014; Žarić et al., 2014). In the current study we focused on the very initial stages of learning to read by examining kindergarten children in their ability to learn letter-speech sound correspondences in an artificial orthography. For this purpose we administered a dynamic learning task and examined 1) whether children at familial risk of dyslexia had more difficulties in learning the new correspondences than their typical-risk peers, and 2) whether this dynamic task was able to predict word reading fluency two years later.

Dyslexia is a specific and significant impairment in the automatic recognition of written words (Fletcher & Lyon, 2008; Peterson & Pennington, 2015; Snowling, 2012). Research indicates that dyslexia is a learning disability of neurobiological origin with a genetic predisposition (Dehaene, 2009; Peterson & Pennington, 2015) that affects approximately 3% to 10% of the population, depending on the precise criteria used for its assessment (Snowling, 2012). Although numerous theories regarding its cause have been proposed (Ramus & Ahissar, 2012), the most commonly accepted hypothesis is that dyslexia stems from a deficit in the phonological processing system (Dehaene, 2009; Vellutino, Fletcher, Snowling, & Scanlon, 2004). According to this hypothesis degraded representation, storage, or retrieval of speech sounds hinders the establishment of proper letter–speech sound mappings, which is the foundation of reading alphabetic languages, resulting in disfluent word recognition (Snowling, 1980; Vellutino, et al., 2004).

While etiological research has focused primarily on identifying and understanding the specific phonological shortcomings that characterize dyslexia, an increasing number of studies published during recent years have addressed the formation of letter-speech sound correspondences (Aravena et al., 2013 -Chapter 3-; Fraga González et al., 2014; McNorgan et al., 2013; Mittag et al., 2013; Nag & Snowling, 2013; Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012; Žarić et al., 2014). Research within this domain slowly starts to unravel what happens in the brain during the process of establishing letter-speech sound correspondences.

In largely transparent orthographies, most children acquire the knowledge of letter–speech sound associations within just months of formal reading instruction (Seymour, Aro, & Erskine, 2003), but there is evidence that automaticity, in the sense that the simple sight of a letter instantaneously activates its phonological representation, takes much longer to develop (Blomert, 2011; Froyen, Bonte, van Atteveldt, & Blomert, 2009; Hahn, Foxe, & Molholm, 2014). It has been suggested that this integration of letter-speech sound correspondences is a prerequisite for the subsequent development of brain areas specialized for fast visual word recognition (Blomert, 2011; Dehaene, Cohen, Morais, & Kolinsky, 2015; McNorgan & Booth, 2015; Preston et al., 2016; Sandak, Mencl, Frost, and Pugh, 2004; Žarić et al., 2014). Evidence from neuroimaging as well as from behavioural studies shows that the automatization of letter-speech sound correspondences requires a prolonged experience-driven tuning process that is still not fully accomplished at the end of primary education (Blomert & Vaessen, 2009; Froyen et al., 2009). Moreover, there is strong evidence that this tuning process is compromised in individuals with dyslexia (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert 2009; Blau et al., 2010; Froyen et al., 2009) even in children with dyslexia that had attained adequate knowledge of these correspondences (Blau et al., 2010; Froyen et al, 2009). Similarly, behavioral studies indicate that children with dyslexia in primary school are outperformed by their typically developing peers on fast letter-speech sound identification despite equal knowledge of the concerning correspondences (Aravena et al., 2013 -Chapter 3-).

In previous studies, we developed a paradigm aimed at learning letter-speech sound correspondences within an artificial orthography (Aravena et al., 2013 -Chapter 3-; Aravena, Tijms, Snellings, & van der Molen, 2015 -Chapter 4-; Aravena, Tijms, Snellings, & van der Molen, 2016 -Chapter 5-). More specifically, this paradigm involves a dynamic assessment that consists of a 20-minute training aimed at learning eight new basic letter-speech sound correspondences, followed by a short assessment of both mastery of the correspondences and word reading ability in this unfamiliar script. The script is artificial in the sense that unfamiliar letters (Hebrew) were used to transcribe participants' native speech sounds. This enabled us to examine the initial steps in learning a novel script without concerns about possible differences in previous exposure to experimental stimuli. The 20-minute training consisted of a computer game in which the child had to match speech sounds to their corresponding orthographic representations. Importantly, our assessment does not involve instruction but just associative learning from contact with the stimuli and implicit feedback. This was done to capture the fundamental ability of mastering letter-speech sound correspondences from mere exposure to sounds and symbols, without interference from more general factors related to instruction, such as intelligence, verbal comprehension, or attention. What we learned so far from our studies (Aravena et al., 2013 -Chapter 3-; Aravena et al., 2015 -Chapter 4-; Aravena et al., 2016 -Chapter 5-) is that: 1) the basic knowledge of the new correspondences was learned equally well by the children with dyslexia and the typical readers; 2) typical readers outperformed children with dyslexia when speech sounds had to be matched to their corresponding letters under time pressure; 3) typical readers outperformed children with dyslexia on the word reading task containing familiar words written in the artificial orthography; 4) all measures from the dynamic assessment made meaningful and partly independent contributions to explaining individual differences in reading and spelling skills; 5) the speed measure from the letter-speech sound identification task made a significant contribution to explaining variance in treatment response on reading accuracy and speed.

In the current study, we extended on the abovementioned findings and applied the dynamic assessment to kindergarten children. We wanted to examine whether, compared to their typical-risk peers, children at risk for dyslexia would perform weaker at learning new letter-speech sound correspondences before the onset of reading instruction, and whether the dynamic assessment was able to predict word reading fluency two years later. Gaining insight into factors that can help identify children at risk for reading difficulties at an early stage is important because it allows for prevention and early intervention. Early efforts to remediate are not only successful, but also reduce the impact of reading difficulties on academic, social, and emotional functioning (Scanlon et al., 2005; Scanlon et al., 2008; Vellutino, Scanlon, & Jaccard, 2003). Some early predictors have been identified, among which letter knowledge (Caravolas et al., 2012; Hulme, Nash, Gooch, Lervåg, & Snowling, 2015) and phonological awareness (Carroll, Mundy, & Cunningham, 2014; Hulme, et al., 2015) are the most common, but, unfortunately, most screening batteries administered before the onset of reading instruction are rather inaccurate (Johnson, Jenkins, Petscher, & Catts, 2009; Peterson, Allen, & Spencer, 2014). Data on potential new predictors is therefore welcome. In the current study a traditional letter knowledge and phonological awareness measure were considered along with the new dynamic assessment of letter-speech sound learning.

Methods

Design

In the current longitudinal study children were assessed at the end of the last year of kindergarten (T1), and two years later, at the end of second grade (T2). At T1, we assessed phonological awareness and letter knowledge, and we applied the DA-procedure which aimed at learning eight new basic letter-speech sound correspondences, followed by a short assessment of the mastery of the correspondences. At T2, word reading in Dutch was assessed.

Participants

Our sample consisted of 28 kindergarten children (13 boys and 15 girls) at familial risk of dyslexia and 28 kindergarten children with normal risk (8 boys and 20 girls). The at-risk children had a mean age of 6.15 years (*SD* = 0.31 months, age range = 5.25 – 6.65 years) and the typical-risk controls had a mean age of 6.12 years (*SD* = 0.27 months, age range = 5,47 – 6,60 years). All participants were healthy kindergarten pupils and were native speakers of Dutch. None of the children had received reading instruction prior to their participation. Parents provided informed consent for their child to participate. The study was approved by the ethical review board of the university.

Children were selected for the at-risk group if at least one older sibling was diagnosed with dyslexia based on the standard criteria for severe dyslexia in the Dutch health care system (Blomert, 2006). The children were recruited from the IWAL Institute, a nation-wide center for learning disabilities in the Netherlands. The typically developing peers were recruited from four different elementary schools from urban areas in the Netherlands. Because we incorporated Hebrew graphemes in our dynamic assessment, previous experience with Hebrew script was an exclusionary criterion.

Dynamic assessment

The dynamic assessment (DA) consisted of a short training that is dedicated to learning non-existent letter-speech sound correspondences followed by an assessment of the mastery of the newly learned correspondences (Aravena et al., 2015 -Chapter 4-; Aravena et al., 2016 -Chapter 5-). The duration of the training was shortened from 20 to 15 minutes to meet with the specific attentional and cognitive demands of kindergarten children. The assessment of word reading ability in the unfamiliar script, which formed part of the DA in previous studies (Aravena et al., 2013 -Chapter 3-; Aravena et al., 2015 -Chapter 4-; Aravena et al., 2016 -Chapter 5-), was left out of the current study because it appeared to be too complex for children without formal reading experience. The total duration of the DA was approximately 25 minutes.

The letter-speech sound training

The training consisted of a computer game in which the child had to match speech sounds to their corresponding orthographic representations (Aravena et al., 2013 -Chapter 3-). Correct associations were rewarded while incorrect associations were penalized. More specific, children operated a cannon at the bottom of the screen, moving it horizontally. The upper part of the screen was composed of balloons containing single graphemes. Children were required to act on speech sounds that were presented repeatedly in the game. Fast playing was reinforced by progressive time restrictions and bonuses for fast playing. The response consisted of releasing bullets that were aimed at the corresponding grapheme. Each time a correct association was made, the balloon disappeared. When children managed to clear a field, a new field of balloons was presented. The game became increasingly complex as the amount of distractor graphemes gradually increased. Figure 1 shows some screenshots from the game.

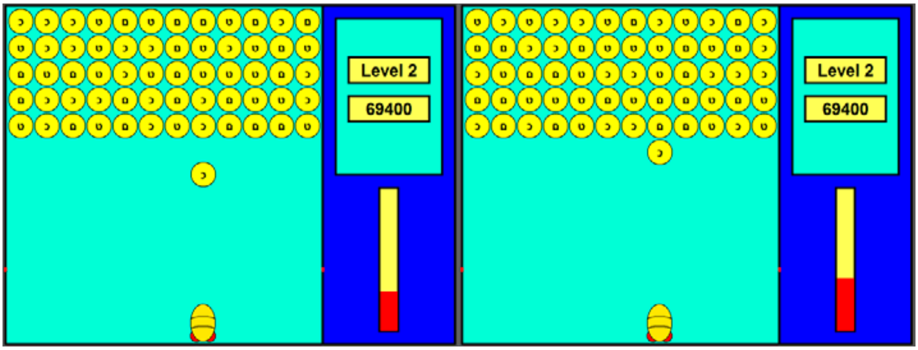


Figure 1 Screenshots from the game

The goal of the training was to learn a set of non-existing letter-speech sound correspondences. At the start of the game the child was presented with a standardized instruction that was integrated in the software. This instruction provided information regarding the specifics of the game but did not reveal the underlying learning objective. After the instruction, children received a short practice trial to become familiar with the set-up and the controls of the game. During the training session children were wearing headphones.

The artificial orthography

The artificial orthography consisted of eight Hebrew graphemes, which were randomly matched to Dutch phonemes, thereby providing eight basic non-existing letter-speech sound pairs. The script represents three vowels and five consonants. Table 1 displays the letter-speech sound correspondences that were used. The directionality of the script was left-to-right.

Letter-speech sound identification task within the artificial orthography

In this task two graphemes from the artificial orthography were displayed at the screen, while simultaneously a phoneme was presented over headphones. By striking the corresponding button the child had to decide, as fast as possible, which of the graphemes matched with the presented phoneme during the training. The task consisted of 56 items. Response speed and accuracy were recorded automatically by the software. The score for response speed was the median speed of correct responses and the score for accuracy was the number of correct responses (reliability respectively *r* = .96 and *r* = .90, split-half).

Table 1:
Letter-speech sound correspondences within an artificial orthography

Letter	ט	כ	ם	ף	פ	צ	ך	ש
Speech sound (IPA)	[u]	[ɛ]	[ɑ]	[k]	[r]	[l]	[t]	[n]

Note: IPA, International Phonetic Alphabet

Traditional measures

Letter knowledge

Receptive letter knowledge was assessed using a task (de Roos, Smit, Steege, & Wagenaar, 2010) that contained 17 different letters representing consonants that are highly frequent in Dutch. The letters were presented in lower case on two cards depicting respectively 8 (n, h, s, r, k, w, b, f) and 9 (d, m, t, l, j, g, z, v, p) letters. One-by-one the experimenter provided each of the sounds, starting with the high-frequency letters, while in response the child was required to point to the corresponding letter on the card. The maximum score is 17.

Phonological awareness

Phonological awareness was assessed with a first sound awareness task (de Roos, Smit, Steege, & Wagenaar, 2010) containing 16 items. Each item consists of a row of four pictures representing high-frequency one-syllable words. In each item the first picture is separated from the other three by a vertical line. The experimenter named all of the pictures and subsequently both the experimenter and the child repeated the word that is represented by the first picture (target word). Then, on each item of the task, children were asked which of the three words represented by the pictures after the line had the same first sound as the target word. In the first four items the experimenter provided the first sound of the target word. From the 5th item onward, the experimenter asked which of the four alternatives started with the same sound as the target word, without naming the sound. The task is preceded by 2 items for practice. The maximum score is 16. The reliability of this task is good (Cronbach's alpha = .85).

Word reading fluency

Word reading fluency was assessed using a standardized Dutch reading test (Three-Minutes-Test; Verhoeven, 1995). This word-reading test includes three different cards of increasing difficulty, containing 150, 150, and 120 words respectively. Children were required to accurately read aloud as many words as possible within one minute for each of the cards. The raw score is determined by the total number of words read correctly over the three cards. In addition to the raw scores we also used standardized scores, based on national normative data, to identify children with reading scores within the lowest quartile and decile. The reliability of the Three-Minutes-Test at the end of Grade 2 is high (r = .97; Krom, Jongen, Verhelst, Kamphuis, & Kleintjes, 2010).

Procedure

At T1, the letter knowledge test, phonological awareness test, and DA-procedure were administered by a trained graduate student on a one-to-one basis and in fixed order. The assessment took place in a silent room at school or in the dyslexia center at the end of kindergarten between May and June.

Word reading at T2 was assessed by a trained teacher at school in June of Grade 2. This assessment was part of the national pupil monitoring system, which consists of periodical testing of academic skills to keep track of pupils' progress. The results from the assessment were provided by the administration of the school after parental consent.

Results

Children at risk for dyslexia versus children with typical risk

The first aim of our study was to examine whether children at risk for dyslexia had more difficulties in learning new letter-speech sound correspondences than their typical-risk peers before the onset of reading instruction. For this purpose we first conducted an independent t-test to determine whether at-risk children and controls differed with regard to the identification of letter-speech sound correspondences in the artificial orthography. The mean scores and standard deviations thus obtained are shown in Table 2. The results indicated that, on average, controls were more accurate on the identification task than the at-risk children, $t(54) = -1.873$, $p < .05$, with a medium effect size ($d = 0.50$). Moreover, the controls responded faster on the same test than the at-risk children, $t(54) = 1.724$, $p < .05$, with a small to medium effect size ($d = 0.46$).

Table 2:
Means and standard deviations

	At-risk (n=28)	Control (n=28)
	M (SD)	*M (SD)*
Letter-speech sound identification accuracy	43.57 (8.36)	47.19 (5.90)
Letter-speech sound identification speed	2228.54 (475.92)	2014.72 (452.72)
Letter knowledge	13.86 (3.59)	15.00 (3.71)
Letter knowledge after transformation	0.451 (0.398)	0.274 (0.383)
Phonological awareness	13.39 (2.53)	14.46 (2.22)
Phonological awareness after transformation	0.444 (0.333)	0.273 (0.326)

To put these results into a broader context we also compared both groups on their performance on two of the most common predictors of reading skill, namely letter knowledge and phonological awareness. As ceiling effects were found for both of these measures, we conducted a log 10 transformation to reduce the skewness. After the transformation the scores were still not normally distributed, but within the critical range of two times the standard error. The results from the independent t-test indicated that the children from the control group outperformed the children from the at-risk group on both letter knowledge, $t(54) = 1.705$, $p = <.05$, with a small to medium effect size ($d = 0.46$), and phonological awareness, $t(54) = 1.931$, $p = < .05$, with a medium effect size ($d = 0.52$).

A correlation analysis was performed to gain insight in how the four different measures relate to each other. The results from this analysis are shown in Table 3. For letter knowledge and phonological awareness the transformed scores were used. Strong correlations were found between the accuracy measure from the identification task, letter knowledge, and phonological awareness. The speed measure from the identification task was not correlated to any of the other measures.

Table 3:
Correlation matrix (N=56)

	1	2	3	4
1 L-SS Identification accuracy (artificial)	1			
2 L-SS Identification speed (artificial)	.080	1		
3 Letter knowledge	-.599**	-.052	1	
4 Phonological awareness	-.633**	-.100	.610**	1

*** significant at the .01 level*

Predicting reading skills at the end of Grade 2

The second aim of our study was to determine whether the dynamic task, when administered in kindergarten, was able to predict word reading fluency at the end of Grade 2. Due to attrition between T1 and T2 the sample was reduced from 56 to 45 subjects. Two families, one from the at-risk group and one from the control group, did not give permission to use the school data. In all other cases we were not able to trace the families (because they had moved or changed schools). Attrition rates were similar for at-risk and control families. Table 4 gives an overview of the reading performance within both groups at the end of Grade 2. The results from an independent t-test indicated that, as expected, children at risk for dyslexia were outperformed on the word reading task by their typical-risk peers, $t(43) = 4.781$, $p < .05$, with a medium to large effect size ($d = 0.65$). Accordingly, children from the at-risk group were overrepresented in the lowest quartile and decile of reading scores.

Table 4:
Reading measures two years later

	At-risk (n=22)	Control (n=23)
	M (SD)	*M (SD)*
Word reading	143.32 (61.18)	182.13 (57.89)
Subjects within lowest 25%	11/22 (50%)	5/23 (21.74%)
Subjects within lowest 10%	8/22 (36,36%)	4/23 (17.39%)

To examine the unique contribution of each of the four predictor variables to individual differences in word reading performance two years later, we employed a series of multiple regression analyses with the word reading score as the dependent variable. The predictor variables were entered in alternating order. For letter knowledge and phonological awareness the transformed scores were used. The results, presented in Table 5, indicated that the accuracy measure from the identification task accounted for a significant proportion of 29% of the variance in word reading at Grade 2. The same was true for phonological awareness and letter knowledge, which, respectively, accounted for 25% and 18% of the variance when entered in the first step. The speed measure from the letter-speech sound identification task did not make a significant contribution.

Tabel 5:
Regression models predicting reading in second grade n=45

Steps		R^2	ΔR^2	β
1	Letter-speech sound identification accuracy	.29	.29***	.34
2	Letter-speech sound identification speed	.31	.02	.15
3	Letter knowledge	.33	.02	-.09
4	Phonological awareness	.36	.02	-.22
1	Phonological awareness	.25	.25***	
2	Letter-speech sound identification accuracy	.33	.08*	
3	Letter-speech sound identification speed	.35	.02	
4	Letter knowledge	.36	.00	
1	Letter knowledge	.18	.18**	
2	Phonological awareness	.27	.09*	
3	Letter-speech sound identification accuracy	.33	.06*	
4	Letter-speech sound identification speed	.36	.02	
1	Letter-speech sound identification speed	.02	.02	
2	Letter knowledge	.22	.20**	
3	Phonological awareness	.30	.07*	
4	Letter-speech sound identification accuracy	.36	.06*	

**** significant at the .001 level*
*** significant at the .01 level*
** significant at the .05 level*

Importantly, neither phonological awareness nor letter knowledge made an additional contribution to explaining variance in word reading at Grade 2 after the accuracy measure from the identification task had been entered in the first step. Notably, only the accuracy measure from the identification task accounted for a unique proportion of variance in each of the regression models.

In addition to the multiple regression analyses, we conducted binary logistic regression analyses and Receiver Operator Characteristic (ROC) curve analyses (Metz, 1978; Swets, 1988) to determine the extent to which the dynamic assessment was able to identify children with reading disabilities at Grade 2 already before the onset of reading instruction. An ROC curve is a plot that illustrates the true positive rate (sensitivity) against the false positive rate (sensitivity – 1) for each of the possible cut-off scores of the predictor. The speed measure of the identification task was left out from these additional analyses, as it did not contribute to variance in word reading in Grade 2. Three cases, two from the at-risk group and one from the control group, were identified as multivariate outliers and were excluded from the analyses because of large standardized residuals (> 2.5) and DFBETAS (measure of the observations' impact on the estimated regression coefficients) exceeding 1, which is considered influential for small to medium sample sizes (Cousineau & Chartier, 2010). Table 6 and 7 contain the results from the logistic regression and ROC curve analyses. The area under the curve (AUC) provides an overall estimate of the predictive power of the assessment. The area under the curve ranges from 0.5 (chance level) to 1.0 (perfect classification). Again, the transformed data were used for letter knowledge and phonological awareness.

Tabel 6:
Binary logistic regression and receiver operating characteristics curve analysis lowest 25%

	Binary logistic regression analysis			ROC curve analysis	
	β	Wald's χ^2	Odds ratio	AUC (95% CI)	SE
L-SS identification accuracy	-.214	9.887**	.808	.862 (.715 – 1.000)***	.075
Letter knowledge	2.810	7.392**	16.617	.740 (.570 – .910)*	.087
Phonological awareness	4.513	10.797**	91.174	.842 (.713 - .970)***	.066

**** significant at the .001 level*
*** significant at the .01 level*
** significant at the .05 level*

Tabel 7:
Binary logistic regression and receiver operating characteristics curve analysis lowest 10%

	Binary logistic regression analysis			ROC curve analysis	
	β	Wald's χ^2	Odds ratio	AUC (95% CI)	SE
L-SS identification accuracy	-.172	7.760**	.842	.828 (.641 - .1000)**	.095
Letter knowledge	3.150	7.361**	23.335	.772 (.595 – .949)*	.090
Phonological awareness	3.407	6.881**	30.181	.788 (.614 - .961)**	.088

*** significant at the .01 level*
** significant at the .05 level*

The results from the logistic regression and ROC curve analyses indicated that both the accuracy measure from the identification task and phonological awareness are successful in identifying children whose word reading scores fall into the first quartile (weakest 25%) at the end of Grade 2. Letter knowledge is a fair predictor. When it comes to predicting which children will fall into the first decile, then the accuracy measure from the identification task is a good predictor and both phonological awareness and letter knowledge are fair predictors. Figure 2 shows a comparison of the AUC values for the three predictors.

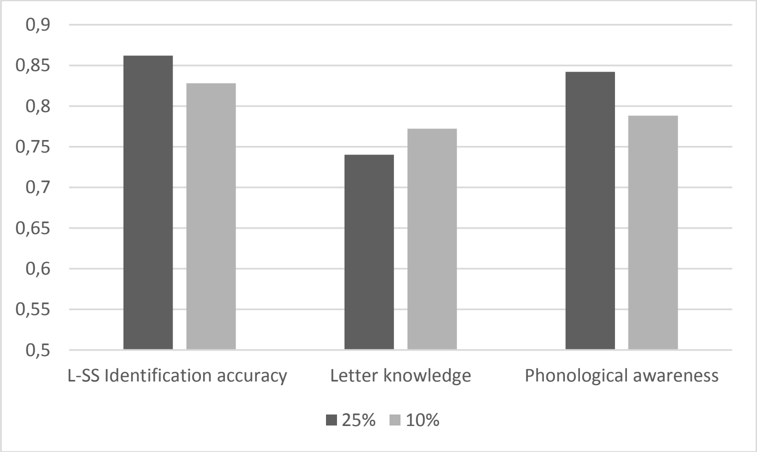


Figure 2 AUC values for the accuracy measure of the letter-speech sound identification task, letter knowledge, and phonological awareness

Discussion

In the current study we examined letter-speech sound learning within an artificial script in kindergarten children. For this purpose we administered a dynamic assessment (DA) consisting of a short computer game in which children were exposed to eight basic letter-speech sound correspondences within an artificial orthography, followed by an assessment of the mastery of these correspondences. We focused on 1) differences in task performance between children at risk of dyslexia and children with typical risk, and 2) the DA's potential to predict reading skill at the end of Grade 2 and to classify in advance those children who will later develop reading difficulties.

Our results indicated significant differences between kindergarten children at risk of dyslexia and their typical-risk peers during the first stages of learning letter–speech sound correspondences. The typical-risk children outperformed the at-risk children with regard to both accuracy and speed on a letter-speech sound identification task. These findings demonstrate that younger siblings of children diagnosed with dyslexia are fundamentally hampered in their ability to learn letter-speech correspondences before the onset of reading instruction at school and suggest that a genetic component is involved in this disability. Our data support the notion that a letter-speech sound learning deficit is key in developing dyslexia (Blau et al., 2010; Blomert, 2011; Mittag et al., 2013; van Atteveldt & Ansari, 2014; Widmann et al., 2012).

In a recent data-driven clustering study, Willems, Jansma, Blomert, and Vaessen (2016) identified letter-speech sound learning as an important independent vulnerability marker for reading disability. In another study, this group observed that a letter–speech sound learning deficit was already present in kindergarten children at familial risk for dyslexia as these children did not gain from a 10-week letter–speech sound training, whereas the controls improved significantly (Blomert & Willems, 2010). To the best of our knowledge, however, studies available to date have not directly tested whether letter-speech sound learning before the onset of reading instruction is a predictor of future reading difficulties. Although many studies identified preliterate letter knowledge as an important predictor of future reading skill (Caravolas et al., 2012; Foulin, 2005) our study is first in demonstrating that the sensitivity for learning letter-speech sound correspondences is a more accurate predictor of later reading fluency and risk for reading difficulties than mere letter knowledge. More specifically, the accuracy measure from the identification task made a significant contribution in explaining variance in word reading two years later. A substantial part of the explained variance was shared with phonological awareness and letter knowledge, but the accuracy measure from the identification task was the only predictor that made a significant contribution over and above the other predictors in all of the regression models.

As we primarily focused on the early identification of children at risk for reading disabilities, we extended the regression analyses with analyses dedicated to classification. The results from these additional analyses indicated that the DA is a useful tool for kindergarten identification of children whose future reading scores will fall within the lowest quartile and even the lowest decile. The area under the curve values for these classifications were .86 and .83 respectively, which is considered good for clinical application (Catts, Nielsen, Bridges, Liu, & Bontempo, 2015). The traditional predictors, phonological awareness and letter knowledge, did reasonably well in identifying children at risk for reading disabilities, but were less accurate than the DA. Our findings are in line with research showing that letter-letter speech sound learning is a significant predictor of reading skill (Aravena et al., 2016 -Chapter 5-; Ehri, 2005; Froyen et al., 2009; van Atteveldt & Ansari, 2014) and with studies indicating that disrupted letter-speech sound learning is associated with dyslexia (Aravena et al., 2013 -Chapter 3-; Fraga González et al., 2014; Mittag, et al., 2013; Moll et al., 2016; Žarić et al., 2014).

A key feature of the current DA instrument is its dynamic nature. Unlike traditional static testing, dynamic testing focuses on learning potential rather than on learning outcome (Gustafson et al., 2014; Grigorenko, 2009). There is ample evidence that dynamic measures might be more successful than static measures in predicting future reading gains (Fuchs, Compton, Fuchs, Bouton, & Caffrey 2011; Gellert & Elbro, 2015; Grigorenko & Sternberg, 1998; Gustafson, Svensson, & Fälth, 2014; but see Caffrey, Fuchs, & Fuchs, 2008). In a recent study, Gellert and Elbro (2015) observed that dynamic assessment of phonological awareness at kindergarten was a more accurate predictor of reading development during the first half of Grade 1 than static phonological awareness, though this advantage disappeared across the second half of Grade 1. Interestingly, in a similar study, Gellert (2015) found that a language-neutral dynamic assessment of decoding at kindergarten contributed significantly to the prediction of children's reading skill at the end of Grade 2 after phonological awareness, letter knowledge, and rapid automatized naming had been controlled for. The dynamic test could not replace the traditional predictors however, as a combination of tests was found to be more predictive of children's reading difficulties than the dynamic test of decoding alone. Our results are consistent with findings from Gellert (2015) and Gellert and Elbro (2015), in that we found support for the view that DA is a powerful tool for predicting learning gains in reading, but in contrast to these studies, the traditional predictors in our study did not add variance after extracting the variance related to DA.

Another advantage of our DA, next to its dynamic nature, is the use of an artificial language, allaying concerns about possible differences in previous exposure to experimental stimuli (Aravena et al., 2013 -Chapter 3-; Taylor, Plunkett, & Nation, 2011). From a more practical perspective, the current DA procedure can be administered fully automatized with the aid of a computer and is suitable for large-scale implementation.

A finding that merits further consideration refers to the observation that the three relevant predictor variables are strongly correlated. In a previous study involving literate children (Aravena et al., 2016 -Chapter 5-), neither accuracy nor speed of performance on the letter-speech sound identification task correlated with phonological awareness. A possible explanation for this apparent inconsistency is that there might be an important difference between preliterate and literate phonological awareness. Phonological awareness assessed in kindergarten children typically involves letter identification or simple synthesis, which is not surprising given that preliterate children cannot yet rely on orthographical representations. Their performance on phonological awareness tasks is most likely to depend on the quality of their letter knowledge. In contrast, the assessment of phonological awareness in literate children generally imposes a demand on more complex decoding and deletion skills. It is assumed that such phonological awareness skills improve along with literacy development or even as a consequence of learning to read (Bishop, 2006; Boets et al., 2010; Castles & Coltheart, 2004; Dehaene et al., 2010; Morais, Cary, Alegria, & Bertelson, 1979). Our observation of a correlation between letter-speech sound learning and phonological awareness in kindergarten children may thus reflect letter-speech sound integration capacity, whereas the absence of a correlation in older children can then be explained by assuming that, in those children, phonological awareness is essentially a product of literacy. This hypothesis could help explain the contradictory findings of studies on the causal relation between phonological awareness and reading development (Castles & Coltheart, 2004; Ziegler & Goswami, 2005).

Our findings revealed that, although the at-risk children and typical-risk children differed in their performance on the speed measure from the letter-speech sound identification task, this measure did not significantly predict later reading performance. In a previous study (Aravena et al, 2016 -Chapter 5-) with older children, involving the same DA procedure, the speed measure was found to be a better predictor of response to reading intervention than the accuracy measure. It should be noted, however, that in that study children performed at ceiling on the accuracy measure. It is therefore possible that in preliterate children poor accuracy is the most important manifestation of deficient letter-speech sound learning while it is speed of performance in older children.

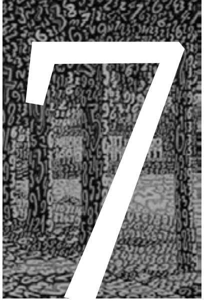
Limitations, prospects, and practical implications

A limitation of the current study is that, although we were able to control for differences in previous exposure to experimental stimuli, children still needed to transcribe phonemes from their native language. Therefore, we were not able to rule out the possibility that children at risk for dyslexia performed weaker due to a less well-specified phonemic framework. Our data thus indicates that compromised letter-speech sound learning precedes reading difficulties, but they cannot establish the exact contribution of phonological awareness to this relation.

Another limitation is that it is difficult to make an unambiguous comparison of the predictive ability of the different measures as both groups performed near ceiling level on the letter knowledge and phonological awareness task. These ceiling effects could have affected the predictive ability of these tasks.

The finding that DA was successful in the early detection of children at risk for reading disabilities has great value, as accurate identification procedures that take place before reading instruction commences, are assumed to be one of the most effective methods to diminish the prevalence of reading disabilities (Petersen et al., 2014) and are considered critical for the prevention of reading disabilities within a Response To Intervention (RTI) framework (Catts et al., 2015). RTI is common practice in educational settings across the United States and several European countries, including the Netherlands, nowadays. With the aim of finding the best possible way to educate children and of identifying children with learning disabilities, the RTI framework provides a pupil with progressively intense and individualized tiers of instruction (Fuchs & Fuchs, 2006; Grigorenko, 2009; Gustafson et al., 2014). Pupils who do not respond to Tier 1 receive more intensive and individualized instruction within Tier 2, and those who are unresponsive to Tier 2 proceed with even more rigorous instruction within Tier 3. Although many pupils benefit from RTI as they receive high-quality instruction as soon as learning difficulties arise, there is a general concern that engaging in less intensive tiers of intervention may not be effective for addressing the reading difficulties of children that are more severely impaired (Denton et al., 2011; Vaughn, Denton, & Fletcher, 2010). From this perspective, children receive instruction within these less intensive tiers only to show their failure in order to gain access to more appropriate instruction (Caffrey et al., 2008; Fuchs et al., 2011; Gustafson et al., 2014; Vaughn et al., 2010). To overcome the apparent limitations of RTI it has been proposed to integrate DA within a RTI framework (Compton et al., 2010; Gustafson et al., 2014; Kantor, Wagner, Torgesen, & Rashotte, 2011; Lidz & Peña, 2009). In this context, our DA may qualify as an alternative or supplement to RTI in future research and policy-making.

In conclusion, our findings indicated that kindergarten children at familial risk of dyslexia performed less well than their typical-risk peers on a DA that measured their sensitivity for learning new letter-speech sound correspondences. Moreover, this DA, administered before the onset of reading instruction, significantly predicted word-reading performance at the end of Grade 2 and identified children at risk for reading disabilities. The DA procedure may therefore provide a useful tool in the early detection of reading disabilities, allowing practitioners to timely adapt their educational strategies for ameliorating reading difficulties in the best possible way and to significantly reduce their impact.



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CHAPTER

General discussion

Aims, background, and main findings

The current dissertation aimed at expanding our knowledge of letter-speech sound learning and its relation to dyslexia, with an emphasis on bridging the gap between fundamental research and educational and clinical practice.

We started our project with a systematic literature review (Chapter 2). Amalgamating insights from cognitive and neurobiological studies, connectionist models, and expert learning, we concluded that massive exposure to letter-speech sound correspondences has a potential catalytic effect on reading fluency. We also concluded that educational computer games provide unique possibilities for establishing this massive exposure.

With the conclusions from our literature review (Chapter 2) in mind, we set up our first empirical study (Chapter 3) in which we focused on the initial learning of letter–speech sound associations, as well as on the influence of type of instructional approach. Children with dyslexia and typical readers engaged in a 1-hour training aimed at learning eight basic letter–speech sound correspondences within an artificial orthography. By adopting an artificial orthography we were able to rule out a-priori differences in exposure to the experimental stimuli. Children from both groups were assigned to one of three different training conditions: (a) explicit instruction, (b) implicit associative learning within a computer game environment, or (c) a combination of (a) and (b) in which explicit instruction was followed by implicit learning. Both letter knowledge and word reading ability within the artificial script were assessed during the training session. This experimental design allowed us to examine the temporal dynamics of letter–speech sound learning. We obtained convincing behavioral evidence for disrupted letter–speech sound learning in dyslexia. Children with dyslexia were outperformed by their peers on a time-pressured binding task and on a word reading task within the artificial orthography. Furthermore, we found support for the added value of implicit learning techniques in promoting letter-speech sound integration in children with dyslexia.

The results that emerged from this first project encouraged us to refine and optimize the training for further study and to make it suitable for the diagnostic assessment of dyslexia. We therefore developed a 30-minute dynamic assessment

(DA), which was used in the subsequent studies. This DA consisted of a 20-minute training that was based on the computer game from the previous study and that was dedicated to learning the artificial orthography, followed by a short assessment of the mastery of the newly learned correspondences. The assessment included a computerized letter-speech sound identification task that directly measured both accuracy and speed of recognition of the learned letter-speech sound correspondences, and a time-limited word-reading task within the artificial orthography.

In the first study involving this DA (Chapter 4), we performed an experimental analysis of letter-speech sound learning in dyslexic and typical readers vis-à-vis phonological awareness, rapid automatized naming, reading, and spelling. Our results indicated that the artificial script-based measures from the DA were related to phonological awareness and rapid automatized naming, and made a unique contribution to the prediction of individual differences in reading and spelling ability as well as in predicting group membership (dyslexic vs. typical readers).

In a subsequent study (Chapter 5) we focused on the prognostic value of the DA and examined its value for predicting responsiveness to reading intervention for children diagnosed with dyslexia. Children diagnosed with dyslexia engaged in specialized intervention during approximately 10 months and their reading and spelling abilities were assessed before and after. Our results indicated that the DA predicted variance in reading skills at posttest, over and above traditional static measures, such as phonological awareness and rapid naming.

The results from the first three empirical studies thus provided strong evidence for compromised letter-speech sound learning in children with dyslexia. As our stimuli involved an artificial orthography it is unlikely that these findings can be attributed to differences in reading experience between the typical readers and the children with dyslexia. However, our paradigm was not able to fully rule out a possible advantage of typical readers having more reading experience. We therefore took the DA one step further and explored letter-speech sound learning in kindergarten children (Chapter 6). More specifically, at the end of kindergarten (T1), we administered our DA to children at familial risk of dyslexia and their typical-risk peers. Word reading fluency was assessed two years later at the end of Grade 2 (T2). Our findings indicated that the at-risk children performed less well on the DA than their peers. Crucially, even though this DA had been administered before the onset of reading instruction, it significantly predicted word-reading performance at the end of Grade 2. Our data thus indicated that compromised letter-speech sound learning is a causal factor in dyslexia that cannot be attributed to differences in reading experience.

Taken together, our findings provide strong empirical support for the view that a letter-speech sound learning deficit is a key factor in developing dyslexia (Blau et al., 2010; Blomert, 2011; Mittag, Thesleff, Laasonen, & Kujala, 2013; van Atteveldt & Ansari, 2014; Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012; Žarić et al., 2015).

An index for efficient letter-speech sound integration

Importantly, our data show that learning to read depends on an individual's skill in learning new letter-speech sound correspondences. We were able to demonstrate that children who benefit most from incidental exposure to letter-speech sound correspondences, in the sense that they learn to accurately and rapidly identify them, learn to read more easily. In contrast, children who profit less are more likely to struggle. Our findings thus imply that there is a fundamental ability to develop a unified percept of this audiovisual information of letters and speech sounds, crucial for fluent reading. It is this ability that, along with exposure to orthography, helps an individual to go beyond the level of learned associations and master these correspondences as integrated audiovisual units and use them automatically in reading. This view is consistent with research indicating a developmental shift from letter-speech sound associations to automatic integration (Blomert, 2011; Froyen, Bonte, van Atteveldt, & Blomert, 2009; Nash et al., 2016). Given the current focus on the initial learning of letter-speech sound correspondences, we were not able to identify this shift in our data, but we did identify a proxy for the developmental trajectory of letter-speech sound learning.

Our empirical studies used 5 different measures related to the artificial script: 1) a letter knowledge task; 2) accuracy during game play; 3) accuracy on the letter-speech sound identification task; 4) speed on the letter-speech sound identification task; and 5) a word reading task (3MAST). We learned from our first empirical study that most of the children in both the dyslexic and typical readers mastered the new correspondences relatively fast, and were able to name all the letters correctly after the short training. This finding fits with the observation that at school most children acquire letter–speech sound associations rapidly and without considerable effort (Blomert & Vaessen, 2009). In contrast, all other measures did differentiate between dyslexic and typical readers. At first sight, it seems surprising to find the accuracy measures to differentiate between the groups given that the letter knowledge task did not. However, as children were encouraged to respond as fast as possible, these measures were in fact not ‘pure’ measures of accuracy. We believe that these measures differentiate, because they relate to the ability to efficiently extract and integrate letter-speech sound correspondences in response to incidental exposure to them (Altieri, Stevenson, Wallace, & Wenger, 2015). It is this index that determines how well children succeed in applying their knowledge of these correspondences in more complex tasks.

The accuracy and speed measures from the letter-speech sound identification task also differentiated between kindergarten children at familial risk of dyslexia and their typical-risk peers, but the effect size for speed was substantially smaller than for accuracy. Accordingly, the speed measure did not significantly predict later reading performance. On the other hand, in the studies with older children (Chapter 4 & 5), the speed measure was found to be a better predictor of variance in current or future reading skill. It should be noted, however, that the older children performed at ceiling on the accuracy measure. Therefore, a plausible explanation for these seemingly contradictory findings would be that in kindergarten children poor accuracy is the most important manifestation of deficient letter-speech sound learning while it is speed of performance in older children. This could also explain why the accuracy and speed measures from the letter-speech sound identification task were not correlated within the group of older children.

Just like the accuracy and speed measures from the letter-speech sound identification task, the word reading task was found to differentiate between dyslexic readers and typical readers. Interestingly, this measure correlated also more strongly to general reading performance than the two measures from the identification task. We believe this finding reflects the fact that in contrast to the measures from the identification task, the performance on the reading task does not only depend on the efficiency of processing letter-speech sound correspondences, but also on decoding skills within a context that does not support fast orthographic pattern recognition.

The above findings led us to conclude that among the three measures from the DA the speed measure from the letter-speech sound identification task is the most adequate proxy for the ability to efficiently integrate letter-speech sound correspondences. For older children the accuracy measure is probably less effective because ceiling levels of performance are reached quickly, whereas the word reading test is less adequate because it appeals to other cognitive skills as well. The results obtained in the third empirical study (Chapter 5) are consistent with this interpretation because they demonstrate that the speed measure from the identification task is the best predictor of treatment success. According to this interpretation, the word reading task is a less adequate predictor because part of its variance is related to factors, as for example decoding skill, that are remedied more easily by the treatment program.

Further theoretical implications: On causality

In general, reading acquisition is an area in which it is difficult to separate causes from consequences. In order to become a skilled reader we engage in many hours of reading instruction and exercise, and, in doing so effectively, we have to rely upon several sensory and cognitive functions. It is therefore not surprising that it is not only the brain that enables reading, but that literacy also profoundly changes the brain. As a result, many of the proposed causes of reading failure, can easily be consequences of reduced reading experience as well (Dehaene, Cohen, Morais, & Kolinsky, 2015; Goswami, 2015).

Accordingly, the fact that our dynamic assessment (DA) is strongly related to reading development does not automatically imply that it is letter-speech sound learning that affects reading performance. It is also possible that the effects of reading experience drive the ability to learn new letter-speech sound correspondences. Indeed, in a recent study (Nash et al., 2016) it has been proposed that compromised letter-speech sound integration could be a consequence of reading level rather than a cause of reading difficulties. Although their data suggest that children diagnosed with dyslexia demonstrate a degree of letter-sound integration that is appropriate for their reading level, this interpretation is seriously challenged by our findings. First, because our paradigm ruled out differences in previous exposure as we adopted an artificial script, and, second, because difficulties with letter-speech sound learning were found to be present before the onset of reading instruction. Based on our data it is therefore more likely that letter-speech sound learning represents the causal factor and reading the consequential. Our findings are consistent with a recent study by Karipidis and colleagues (2016) in which they found that in preliterate children the degree of audiovisual integration in a distributed brain network depended on the learning rate during a short training of non-existent letter-speech sound pairs and, moreover, correlated with familial risk for dyslexia.

Phonological processing skills and dyslexia

A theoretical model that has particularly dominated causal accounts of dyslexia over the past 30 years, is the phonological deficit hypothesis. According to this hypothesis degraded representation, storage, or retrieval of speech sounds hinders the establishment of proper letter–speech sound mappings resulting in disfluent word recognition (Snowling, 1980; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Although there is a large body of strong and convergent evidence in support of a phonological deficit in individuals diagnosed with dyslexia (Dehaene, 2009; Peterson & Pennington, 2015; Vellutino et al., 2004), its causal status continues to be debated (Blomert & Willems, 2010; Castles & Coltheart, 2004; Castles, Wilson, & Coltheart, 2011; Hulme, Snowling, Caravolas, & Carroll, 2005; Morais, Cary, Alegria, & Bertelson, 1979; Perfetti, Beck, Bell, & Hughes, 1987; Ziegler & Goswami, 2005). More specifically, it has been argued that phonological processing skills may develop as a consequence rather than as a precursor of reading acquisition, and, in line with this, that there is still no convincing evidence that phonological awareness precedes and directly influences reading acquisition (Blomert & Willems, 2010; Castles & Coltheart, 2004; Castles, Coltheart, Wilson, Valpied, & Wedgwood, 2009; Morais et al., 1979; Morais & Kolinsky 2005; Perfetti et al., 1987). This view is empirically supported by research indicating that unschooled illiterate adults show poor phoneme awareness (de Santos Loureiro et al., 2004) and that performance on phonological awareness tasks improves when these illiterate adults learn to read (Morais et al., 1979). Similarly, Read, Zhang, Nie, and Ding (1986) found that Chinese readers who had learned to read logographically performed more poorly on phonological awareness tests than those who had learned to read alphabetically (pinyin). Further support comes from studies with children at familial risk for dyslexia (Blomert & Willems, 2010; Castles et al, 2009). In one such study Castles and colleagues (2009) found that 6 weeks of phonemic awareness training improved phonemic awareness, but did not directly assist preliterate children in the subsequent acquisition of reading skills.

In support of a causal relation between phonological processing skills and reading, longitudinal studies found several indices of phonological competence, among which phonological awareness and rapid naming, measured before school age to be predictive of future reading skill (Lyytinen, Erskine, Hämäläinen, Torppa, & Ronimus, 2015; Maurer, Bucher, Brem, & Brandeis, 2003; Pennington & Lefly, 2001; Storch & Whitehurst, 2002 Torppa, Lyytinen, Erskine, Eklund, & Lyytinen, 2010). Moreover, training and intervention studies indicate that dyslexic readers show improvements in word identification, spelling, and reading ability in general after phonological training (Scanlon, Vellutino, Small, Fanuele, & Sweeney, 2005; Torgesen et al., 2001; Vellutino et al., 1996)

Given the current state of affairs in which some data seem to indicate that phonological skills enable or assist literacy acquisition, while other findings indicate that causality flows in the opposite direction, a now commonly accepted view is that at least there must be some sort of complex reciprocal relationship between the two (Anthony & Francis, 2005; Peterson & Pennington, 2015).

Although our paradigm was not primarily intended to contribute to the discussion on the causal relation between phonology and reading, we do believe our data call into question some of the claims made by the phonological deficit hypothesis. As indicated earlier, an important assumption of this theory is that phonological impairments hinder the establishment of proper letter–speech sound mappings, resulting in disfluent word recognition. Notably, our data seriously challenge this view. First, because letter-speech sound identification within the artificial orthography was not found to be correlated to phonological awareness, and, second because the measures related to the artificial orthography contributed uniquely to the variance in reading and spelling skills. Moreover, in the third study (Chapter 5) our results indicated that letter-speech sound learning predicted the success of specialized reading intervention over and above phonological awareness. Finally, in the fourth study (chapter 6) a letter-speech sound integration deficit was already found in kindergarten children at familial risk of dyslexia and was a superior predictor of word reading fluency two years later. Therefore, it rather seems that disrupted letter-speech sound learning is at least a partly independent factor underlying dyslexia.

An interesting hypothesis that emerges from our findings is that there might be a fundamental difference between preliterate and literate phonological awareness. This idea originates from the observation that letter-speech sound learning and phonological awareness were strongly correlated in the fourth study (Chapter 6), featuring kindergarten children, while no correlation between these measures was found in the studies involving literate children. We concluded that this apparent inconsistency might have been caused by a different operationalization of phonological awareness tasks for preliterate children compared to literate children. Phonological awareness assessed in kindergarten typically involves letter identification or simple synthesis, since preliterate children cannot yet rely on orthographic representations. Their performance on phonological awareness tasks is most likely to depend on the quality of their letter knowledge. In contrast, the assessment of phonological awareness in literate children generally imposes a demand on more complex decoding and deletion skills, and, as mentioned, it is assumed that such phonological awareness skills improve along with literacy development or even as a consequence of learning to read (Bishop, 2006; Boets et al., 2010; Castles & Coltheart, 2004; Dehaene et al., 2010; Morais et al., 1979). Thus, according to this view phonological awareness is essentially a product of literacy, and manifestations of phonological shortcomings before the onset of reading instruction are largely a result of poor letter-speech sound learning.

This hypothesis in which literate and preliterate phonological awareness are considered to be different things, could help explain the contradictory findings of studies on the causal relation between phonological awareness and reading development (Castles & Coltheart, 2004; Ziegler & Goswami, 2005) Interestingly, it could also provide an answer to the question why most individuals diagnosed with dyslexia remain disfluent readers, even when their phonological awareness and word decoding skills are adequate (Biancarosa & Snow, 2004; Blomert, 2011), namely, that it is poor letter-speech sound learning that primarily hinders fluent reading and not poor phonological awareness. This line of thought is further supported by a recent study by Žarić and colleagues (2014) who found that reduced neural integration of letter-speech sound correspondences in children diagnosed with dyslexia correlates with individual differences in reading fluency. Moreover, other findings indicate that children with dyslexia show substantial gains in reading fluency in response to an intensive training of letter-speech sound mappings (Fraga González et al., 2015; Žarić et al., 2015).

Letter-speech sound learning and rapid automatized naming

How does letter-speech sound learning relate to rapid automatized naming (RAN) and what can our results tell us about the mechanisms that are responsible for the relation between rapid naming and reading? In our second empirical study (Chapter 4) we found RAN to be strongly related to the speed measure of the letter-speech sound identification task within the artificial orthography. This finding was particularly interesting because the tasks were unrelated to phonological awareness and, most importantly, were orthographically dissimilar. The correlation could therefore not be explained by phonological or orthographical factors. Moreover, our paradigm enabled the exclusion of other factors that have regularly been put forward as potential mediators between RAN and reading, such as general processing speed, serial processing, and articulation (Georgiou, Parrila, & Papadopoulos, 2016; Kirby, Georgiou, Martinussen, & Parrila, 2010). We therefore concluded that the observed correlation must have originated from some other source, a source that might also be responsible for the relationship between rapid naming and reading. A plausible candidate for this source is the earlier mentioned proxy for letter-speech sound learning, a fundamental ability to effectively extract audiovisual information from incidental exposure to relevant stimuli. According to this view, poorly integrated letter-speech sound mappings lead to slow and laborious naming of alphanumeric material, and, following from this, to poor reading as well. On this account, it is the extent to which letter-speech sound correspondences are automatized that mediates between rapid naming and reading proficiency. This interpretation is consistent with the view put forward by Bowers and Wolf (1999), who suggested that disturbed naming speed may result in reading failure because of impeded amalgamation of connections between phonemes and orthographic patterns. It is also consistent with the observation that RAN involving alphanumeric symbols is more strongly related to reading than RAN with nonalphabetic stimuli, such as colors and pictured objects (Norton & Wolf, 2012; van den Bos, Zijlstra, & van den Broeck, 2003), because the latter stimuli are less likely to directly depend on letter-speech sound learning.

In sum, our data challenges some of the assumptions of the current etiological framework of dyslexia, and support the view that the causal influence of phonological awareness and RAN on reading acquisition might be overestimated. Our data rather suggest that performance on phonological awareness and RAN tasks at least partly depends on letter-speech sound learning ability and reading proficiency.

Practical implications

We believe that our findings provide an important message for practitioners as well as opportunities for the development and implementation of new tools for assessment and remediation. Most importantly, our findings plead for a more prominent role for letter-speech sound learning in educational and clinical practice.

Based on the conclusions concerning fluency-oriented instructional practices we drew from our literature review (Chapter 2), we proposed several new directions for dyslexia treatment. Most importantly, we stressed the fact that efficient processing of grapheme-phoneme correspondences is a key aspect in fluent reading acquisition and advocated extensive training of these correspondences until they are really well anchored in the brain. We furthermore argued that this extensive exposure should take place simultaneously with explicit instruction and that the focus must first lie on isolated phonemes and then slowly be shifted towards increasingly larger word fragments and ultimately whole words, mirroring the developmental trajectory and hierarchical organization of relevant brain mechanisms. These arguments were supported in our first empirical study (Chapter 3), in which we found evidence for the added value of implicit learning techniques in promoting letter-speech sound integration in children with dyslexia and its influence on reading. The findings from the third empirical study (Chapter 5) also plead for a stronger focus on letter-speech sound correspondences during treatment. The fact that the DA, based on the ability to learn letter-speech sound correspondences, predicts responsiveness to reading intervention indicates that it is especially that factor that limits potential growth in reading. Further confirmation from a clinical setting came from recent research indicating that intensive training of letter-speech sound integration improves reading fluency in children with dyslexia (Fraga González et al., 2015).

Another conclusion we drew from our literature review (Chapter 2) and that could be valuable for practice, is that edugames provide unique possibilities to effectuate the intended extensive training of letter-speech sound correspondences. These games, which are designed to teach certain skills, can be controlled automatically and can provide large amounts of audiovisual stimuli within a short period of time. Moreover, motivation can be sustained at high levels, and learning dynamics can easily be adapted to the pupils needs. If the game is designed in such a way that educational aspirations coincide with game objectives, a form of associative learning arises which is highly effective.

In an attempt to translate these scientific insights into real-life solutions, we developed an edugame named LexyLink, that aimed at extensive training letter-speech sound correspondences. The findings from the first empirical study (Chapter 3) clearly indicated that the game was effective in teaching these correspondences, both in children diagnosed with dyslexia and typical readers. Interestingly, the game did not involve learning from instruction but just from incidental exposure and implicit feedback. This finding is important because it demonstrates that adding implicit training to explicit instruction is an efficient way of optimizing exposure. Notably, dyslexic readers are in strong need of print exposure (Thaler, Ebner, Wimmer, & Landerl, 2004; Torgesen, 2005) and the amount of hours that can be invested in explicit instruction, within a given period of time, is restrained by cognitive load. Edugames could thus counteract the limitations imposed by cognitive load.

Another insight from the first empirical study (Chapter 3) is that a combination of explicit instruction and implicit techniques provides a more powerful tool in the initial teaching of letter–sound correspondences than implicit training alone. This finding has implications for clinical practice because there is a tendency to exchange traditional explicit techniques for implicit techniques, which are based mainly on associative learning and extensive exposure and which make use of a computer game environment (Lovio, Halttunen, Lyytinen, Näätänen, & Kujala, 2012; Lyytinen, 2008; Saine, Lerkkanen, Ahonen, Tolvanen, & Lyytinen, 2011). Our data indicate that we need to be cautious to abandon explicit instruction. Moreover, when it comes to learning an algorithmic rule in reading and spelling, it seems that explicit instruction is even more crucial. None of the children engaging solely in the game was able to deduce the orthographical rule by himself or herself.

Identification and assessment

The findings from the next three empirical studies (Chapter 4, 5, and 6) mainly have practical implications for the identification of poor readers and the assessment of dyslexia. Most importantly, we found that a short DA procedure that focuses on letter-speech sound learning within an artificial orthography, makes a valuable contribution to the identification of reading disability at school and to the assessment of dyslexia. More specifically, our data indicates that the DA: 1) contributes meaningfully and partly independently to explaining individual differences in reading and spelling skills; 2) differentiates between children at familial risk of dyslexia and their typical-risk peers; 3) differentiates between children diagnosed with dyslexia and typical readers; 4) makes a significant contribution to explaining variance in treatment response on reading accuracy and speed; and 5) predicts word-reading performance at the end of Grade 2, when administered before the onset of reading instruction. Collectively, these findings indicate that a combination of conventional testing and our DA constitutes a stronger prediction of individual differences in reading and spelling skills than conventional testing alone. Accordingly, conventional testing augmented with DA would provide a substantial improvement of the assessment of dyslexia. Moreover, the DA provides a useful tool for identifying children at risk for reading disabilities already in kindergarten, allowing practitioners to timely adapt their educational strategies for ameliorating reading difficulties in the best possible way and to significantly reduce their impact.

A finding that merits further consideration is that DA has the potential to predict responsiveness to intervention within a sample of children diagnosed with dyslexia. This is of particular interest because the quest for predictors of responsiveness to intervention for this group has not been very fruitful (Frijters et al., 2011; Hoeft et al., 2011; Tijms, 2011). Our results indicate that a dynamic approach to assessment provides new opportunities to predict responsiveness to intervention even for the most reading disabled. From a clinical perspective, early identification of potential non-responders is valuable because it may assist practitioners in adapting their educational strategies at an initial stage or even start off a prompt deployment of alternative ways of accessing written information, such as computer-based reading.

A closer look at Dynamic Assessment

Given the positive results regarding the DA procedure it is relevant to consider its specific strengths and distinctive features. An important characteristic of the DA procedure is that it refers to learning artificial letter-speech sound correspondences. This implies that there are no a-priori differences in exposure to the stimuli at the start of the assessment. In this respect, the training would provide a relatively ‘pure’ assessment compared to traditional instruments, in the sense that the typical reciprocity between reading development and phonological development is circumvented. Traditional tests can be used to determine if letter-speech sound correspondences are weak, but they do not tell whether this should be attributed to a predisposition, to reading problems, to differences in exposure, or to a combination of these factors. In contrast, the current learning procedure allows for the detection of a fundamental learning deficit for letter-speech sound associations.

Another key feature of the DA procedure is its implicit focus. As our assessment does not involve explicit instruction but just associative learning from exposure and implicit feedback, there is less interference from more general factors related to instruction, such as intelligence, verbal comprehension, or attention.

A third distinctive aspect of the tool is that it is dynamic in nature. Unlike traditional static testing, dynamic testing focuses on learning potential rather than on learning outcome (Gustafson, Svensson, & Fälth, 2014; Grigorenko, 2009). There is ample evidence that dynamic measures might be more successful than static measures in predicting future reading gains (Fuchs, Compton, Fuchs, Bouton, & Caffrey 2011; Gellert & Elbro, 2015; Grigorenko & Sternberg, 1998; Gustafson et al., 2014; but see Caffrey, Fuchs, & Fuchs, 2008). We believe that a particular strength of our DA is that it not only identifies an essential underlying factor, that is a letter–speech sound binding deficit, but that, due to its dynamic nature, it also provides an index of the extent to which this underlying problem interferes with learning to read.

Dynamic assessment and response to intervention

From a broader perspective our findings concerning the DA may be valuable within the context of response to intervention (RTI; Fuchs & Fuchs, 2006; Grigorenko, 2009; Gustafson et al., 2014). Although many pupils benefit from RTI as they receive high-quality instruction as soon as learning difficulties arise, the notion that intervention should initially be of modest intensity has been questioned (Denton et al., 2011; Vaughn, Denton, & Fletcher, 2010). Especially the value of Tier 2 intervention for the most learning disabled continues to be subject to debate (Compton et al., 2012; Fuchs, Fuchs, & Compton, 2010). Indeed, there is evidence that engaging in less intensive tiers of intervention may not be effective for addressing the reading difficulties of children with dyslexia (Vaughn et al., 2010). Early identification of non-responders could thus potentially improve their chance to benefit from intervention by intensifying initial intervention. Accordingly, it has been proposed to integrate DA in a RTI framework to overcome the apparent limitations of RTI (Compton et al., 2010; Gustafson et al., 2014; Kantor, Wagner, Torgesen, & Rashotte, 2011; Lidz & Peña, 2009). Especially the finding that our DA predicts the response to intervention before the actual intervention commences, supports the utility of DA in RTI decision-making. It allows for skipping tiers of less intensive intervention or even for starting specialized intervention right away. Importantly, the DA can be administered fully automatized and is therefore suitable for large-scale implementation. The finding that our DA is successful in the early detection of children at risk for reading disabilities has great additional value, as accurate identification procedures that take place before reading instruction commences, are assumed to be one of the most effective methods to diminish the prevalence of reading disabilities (Petersen, Allen, & Spencer, 2014) and are considered critical for the prevention of reading disabilities within a RTI framework (Catts, Nielsen, Bridges, Liu, & Bontempo, 2015).

In sum, we believe that the kind of process-oriented testing we introduced would be a welcome complement to the practitioner's toolbox, both in educational and clinical settings. It has proven its added value for early identification, diagnostic assessment, and prognostics, and can be valuable for RTI decision-making.

Challenges and limitations

Some comments on limitations are in order. First, it is important to note that our paradigm was not designed to disentangle the causal relationship between letter-speech sound learning and phonological awareness. In this regard, we are not able to make strong claims concerning this issue. Although, by adopting an artificial orthography, we were able to control for differences in previous exposure to experimental stimuli, children still needed to transcribe phonemes from their native language. Therefore, we were not able to rule out the possibility that dyslexic readers were put at a disadvantage due to a less well-specified phonemic framework. We do believe, however, that the phonological deficit hypothesis does not provide an unequivocal interpretation of our findings. In this regard, our findings present a serious challenge to the current theoretical framework of dyslexia. More specifically, the view that phonological impairments hinder the establishment of proper letter–speech sound mappings was questioned by the current observation that letter-speech sound identification within the artificial orthography was not associated with phonological awareness.

Another limitation is that the current dissertation exclusively focuses on the Dutch language. Accordingly, we cannot unambiguously generalize our findings to other languages. Languages vary considerably in the consistency with which speech sounds are represented in orthographic symbols due to which some languages bring forth more difficulties to individuals with dyslexia than others (Landerl et al., 2013; Seymour, Aro, & Erskine, 2003; Siegler & Goswami, 2005). Notably, in a recent study letter-speech sound integration was found to be moderated by orthographic depth and letter-speech sound correspondences were shown to be less overlearned in English readers than in Dutch readers (Holloway, van Atteveldt, Blomert, & Ansari, 2013).

Bridging research and education

An important impetus for the current dissertation was the desire to go beyond the level of providing useful suggestions for educational and clinical practice, and to actually translate our findings into real-life solutions. Therefore, we started a project in which we developed a serious game for large scale application in education and health care. This game, called Kosmos Klikker (Cosmos Clicker), is based on LexyLink and on the insights we obtained from the different studies within this dissertation. Kosmos Klikker is a highly engaging game in which, by associative learning, children get familiarized with all phonemes (44) in the Dutch language. Figure 1 depicts some screenshots from the game. As the game provides large amounts of audiovisual exposure to letter-speech sound correspondences, it is aimed at boosting letter-speech sound integration rather than increasing speech sound knowledge. Kosmos Klikker is adaptive in the sense that stimuli that attract errors and slower response rates are presented more often. It is also designed to be adaptive on type of error, that is, on the probability of a letter to be misidentified as a match for a given speech sound. These misidentified letters will temporarily be presented more frequently as ‘distractor’. Another important feature is that the game displays a variety of intonation patterns for each phoneme, just as phonemes are pronounced differently in real life. Finally, Kosmos Klikker monitors progress, including response latencies, and amount of playing time for each player and educational practitioners can access these data via a back-office tool. Currently, Kosmos Klikker serves as an add-on to specialized dyslexia treatment in the Netherlands and is being deployed by a growing number of schools throughout the country. Within school settings the game is used as a preventive tool for children in kindergarten and as a treatment tool for children in Grade 1 and 2 of elementary school.

Interestingly, based on our findings, we also developed a dynamic assessment tool for practical application. This tool is integrated in Kosmos Klikker, and consists of a fixed 15-minute game in which the child is exposed to eight non-existing letter-speech sound correspondences followed by a short evaluation of learning progress. The large-scale application of this dynamic assessment will generate substantial amounts of data in the near future, and this data will be used for further scientific research and for optimizing the predictive potential of the tool.

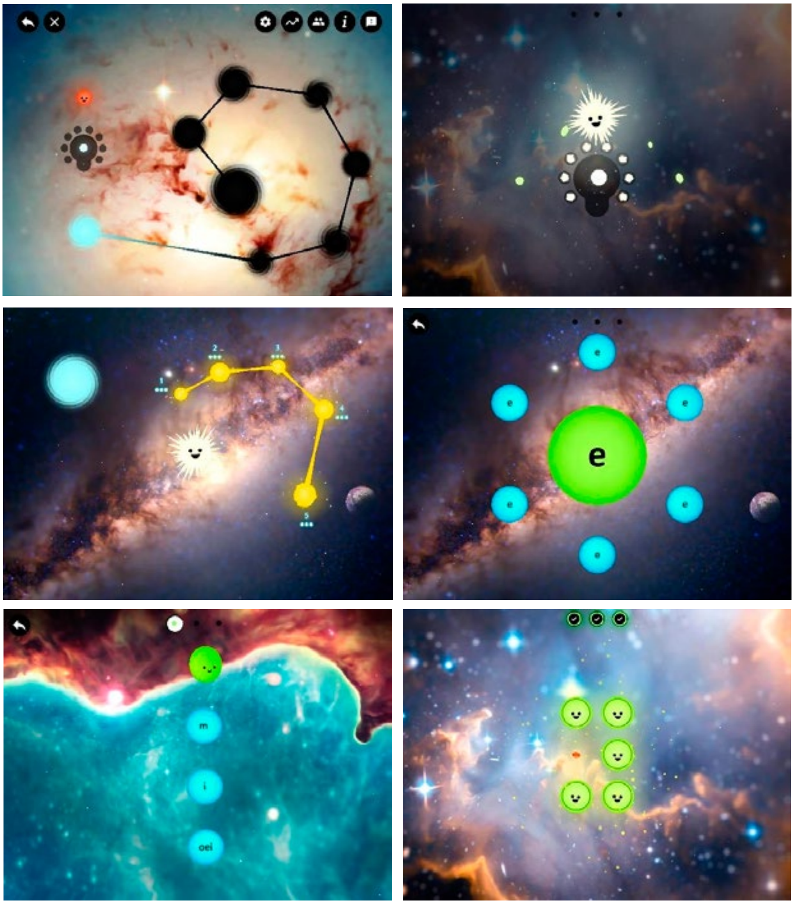


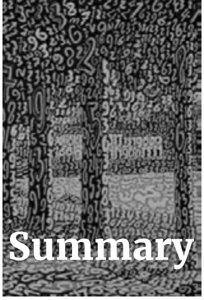
Figure 1 Screenshots from the serious game Kosmos Klikker

Looking forward

Although we have learned a great deal from the studies within the current dissertation, research on letter-speech sound learning is still in its infancy. Accordingly, many questions remain to be explored. We will therefore carry forward our paradigm and hope that our research will also inspire others to apply the artificial orthography paradigm to further elucidate the nature of letter–speech sound binding and its relation to reading development.

Obviously, the large-scale implementation of Kosmos Klikker will provide us with considerable amounts of relevant data for new research. Moreover, we will continue to evaluate the effect of the addition of Kosmos Klikker to specialized treatment. Furthermore, we will continue to follow the children from our longitudinal study and interpret their future reading and spelling scores in the light of the data we have already collected. In line with this, it will be of interest to see which children from the at-risk group will eventually be diagnosed with dyslexia.

An important goal for future research is to extend our paradigm by including electrophysiological and neuroimaging measures in order to complement our findings from behavioral studies with neurocognitive data. Lastly, we would like to stress that our DA procedure is not restricted to a specific language. Hence, we will use it for cross-linguistic research on dyslexia. A universal measure for assessing the strength of letter-speech sound learning could also be adopted for diagnosing dyslexia in a second language. This is of considerable importance because standard reading and spelling measures, as well as phonology-related measures, usually fall short in disentangling the confounding influence of lower language proficiency in the second language (Elbro, Daugaard, & Gellert 2012).



Summary

The current dissertation aimed at expanding our knowledge of letter-speech sound learning and its relation to dyslexia, with an emphasis on bridging the gap between fundamental research and educational and clinical practice.

We started our project with a systematic literature review (Chapter 2). Amalgamating insights from cognitive and neurobiological studies, connectionist models, and expert learning, we concluded that massive exposure to letter-speech sound correspondences has a potential catalytic effect on reading fluency. We also concluded that educational computer games provide unique possibilities for establishing this massive exposure.

With the conclusions from our literature review (Chapter 2) in mind, we set up our first empirical study (Chapter 3) in which we focused on the initial learning of letter–speech sound associations, as well as on the influence of type of instructional approach. Children with dyslexia and typical readers engaged in a 1-hour training aimed at learning eight basic letter–speech sound correspondences within an artificial orthography. By adopting an artificial orthography we were able to rule out a-priori differences in exposure to the experimental stimuli. Children from both groups were assigned to one of three different training conditions: (a) explicit instruction, (b) implicit associative learning within a computer game environment, or (c) a combination of (a) and (b) in which explicit instruction was followed by implicit learning. Both letter knowledge and word reading ability within the artificial script were assessed during the training session. This experimental design allowed us to examine the temporal dynamics of letter–speech sound learning. We obtained convincing behavioral evidence for disrupted letter–speech sound learning in dyslexia. Children with dyslexia were outperformed by typical reading peers on a time-pressured binding task and on a word reading task with the artificial orthography. Furthermore, we found support for the added value of implicit learning techniques in promoting letter-speech sound integration in children with dyslexia.

The results that emerged from this first project encouraged us to refine and optimize the training for further study and to make it suitable for the diagnostic assessment of dyslexia. We therefore developed a 30-minute dynamic assessment (DA), which was used in the subsequent three studies. This DA consisted of a 20-minute training that was based on the computer game from the previous study and that was dedicated to learning the artificial orthography, followed by a short assessment of the mastery of the newly learned correspondences. The assessment included a computerized letter-speech sound identification task that directly measured both accuracy and speed of recognition of the learned letter-speech sound correspondences, and a time-limited word-reading task within the artificial orthography.

In the first study involving this DA (Chapter 4), we performed an experimental analysis of letter-speech sound learning in dyslexic and typical readers vis-à-vis phonological awareness, rapid automatized naming, reading, and spelling. Our results indicated that the artificial script-based measures from the DA were related to phonological awareness and rapid automatized naming, and made a unique contribution to the prediction of individual differences in reading and spelling ability as well as in predicting group membership (dyslexic vs. typical readers).

In a subsequent study (Chapter 5) we focused on the prognostic value of the DA and examined its value for predicting responsiveness to reading intervention for children diagnosed with dyslexia. Children diagnosed with dyslexia engaged in specialized intervention during approximately 10 months and their reading and spelling abilities were assessed before and after. Our results indicated that the DA predicted variance in reading skills at posttest, over and above traditional static measures, such as phonological awareness and rapid naming.

The results from the first three empirical studies thus provided strong evidence for compromised letter-speech sound learning in children with dyslexia. As our stimuli involved an artificial orthography it is unlikely that these findings can be attributed to differences in reading experience between the typical readers and the children with dyslexia. However, our paradigm was not able to fully rule out a possible advantage of typical readers having more reading experience. We therefore took the DA one step further and explored letter-speech sound learning in preliterate children (Chapter 6). More specifically, at the end of kindergarten, we administered our DA to children at familial risk of dyslexia and their typical risk peers. Word reading fluency was assessed two years later at the end of Grade 2. Our findings indicated that the at-risk children performed less well on the DA than their typical peers. Crucially, even though this DA had been administered before the onset of reading instruction, it significantly predicted word-reading performance at the end of Grade 2 and also identified children with below average reading scores at the end of Grade 2. Our data thus indicated that compromised letter-speech sound learning is a causal factor in dyslexia that cannot be attributed to differences in reading experience.

Taken together, our findings confirm that there is a fundamental difference between letter knowledge and automatic letter-speech sound integration, provide strong empirical support for the view that a letter-speech sound learning deficit is a key factor in developing dyslexia, and plead for a more prominent role for letter-speech sound learning in educational and clinical practice.

In het kort

Het leren van de correspondenties tussen de klanken uit onze taal en de letters die we gebruiken om ze weer te geven, ook wel klank-tekenkoppelingen genoemd, is een cruciale stap in onze leesontwikkeling. Het doel van de studies in deze dissertatie was enerzijds om onze kennis van het leren van deze koppelingen te vergroten en anderzijds om meer te weten te komen over de relatie tussen dit leerproces en dyslexie. In een poging een brug te slaan tussen wetenschap en praktijk, richtten de studies zich in het bijzonder op concrete toepassingen voor onderwijs en zorg.

Vanuit mijn praktijkervaring heeft het mij altijd gefrustreerd dat het zelfs met de meest succesvolle behandeltechnieken slechts in beperkte mate lukt mensen met dyslexie vloeiend te laten lezen. In de hoop bij te dragen aan het vinden van de sleutel die deze impasse zou doorbreken, startte ik mijn dissertatie met een systematisch literatuuronderzoek (Hoofdstuk 2). Dit onderzoek bracht mij tot het inzicht dat: 1) zeer intensieve blootstelling aan klank-tekenkoppelingen een potentieel gunstig effect heeft op de vloeiendheid van het lezen; en 2) de inzet van computerspellen die zich richten op leren, unieke mogelijkheden biedt om deze zeer intensieve blootstelling te bewerkstelligen.

Met deze inzichten in mijn achterhoofd startte ik met mijn collega's een eerste empirische studie (Hoofdstuk 3) waarin het aanvankelijk leren van letter-klankkoppelingen centraal stond, alsook de invloed van de manier waarop deze koppelingen worden aangeleerd. In deze studie kregen kinderen die gediagnosticeerd waren met dyslexie en normale lezers een training van een uur waarin ze acht klank-tekenkoppelingen leerden uit een niet-bestaand schrift. Door gebruik te maken van een niet-bestaand schrift konden we a priori verschillen in blootstelling aan de te leren koppelingen uitsluiten. Kinderen uit beide groepen werden willekeurig verdeeld over drie condities: (a) expliciete instructie; (b) incidenteel leren aan de hand van een computerspel; of (c) een combinatie van (a) en (b) waarin expliciete instructie voorafging aan incidenteel leren. Tijdens en na de training werden letterkennis en leesvaardigheid in het artificiële schrift gemeten. We vonden geen verschil tussen de groepen in letterkennis, maar onder tijdsdruk bleken de kinderen met dyslexie significant meer fouten te maken met het koppelen van klanken aan letters en ook op de leestaak presteerden de normale lezers significant beter. Deze bevindingen gaven aanwijzingen voor een verstoord vermogen om klank-tekenkoppelingen te leren bij kinderen met dyslexie. Verder vonden we dat kinderen in alle condities het schrift leerden, maar dat de twee condities met expliciete instructie een hoger leerrendement gaven dan de incidenteel leren conditie. Het feit dat kinderen met dyslexie ook klank-tekenkoppelingen leren door het spelen van een computerspel, zoals in de incidenteel-leren-conditie het geval was, is van groot belang omdat het de mogelijkheid biedt behandeling verder te intensiveren zonder dat dit tot motivatieverlies of overbelasting leidt.

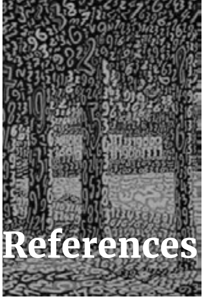
De bevindingen van deze eerste experimentele studie stimuleerden ons om verder onderzoek te doen met de incidenteel-leren-training en deze om te vormen tot een diagnostische tool. Dit resulteerde in een halfuur durende dynamische test die centraal zou staan in de volgende studies. De dynamische test bestond uit een korte training (20 minuten) waarin kinderen met behulp van het eerdergenoemde computerspel acht klank-tekenkoppelingen uit het artificieel schrift leerden en een evaluatie van het leerresultaat. Tijdens de evaluatie werd aan de hand van een computertaak zowel de accuratesse als snelheid gemeten waarmee kinderen de geleerde koppelingen konden identificeren. Ook werd de leesvaardigheid in het artificiële schrift gemeten met een tijdgebonden woordleestaak.

In een tweede experimentele studie (Hoofdstuk 4), waarin de dynamische test centraal stond, hebben we gekeken naar hoe het leren van letter-klankkoppelingen zich verhoudt tot de lees- en spellingvaardigheid, alsook tot leesgerelateerde cognitieve maten, zoals fonologisch bewustzijn en snelheid van benoemen. De resultaten lieten zien dat de prestaties op de dynamische test 1) significant correleerden met fonologisch bewustzijn en snelheid van benoemen; 2) een unieke bijdrage leverden aan het verklaren van individuele verschillen in lees- en spellingvaardigheid; en 3) boven kansniveau voorspelden tot welke groep de kinderen behoorden (dyslexie versus normale lezers).

In de volgende studie (Hoofdstuk 5) richtten we ons op de prognostische waarde van de dynamische test en onderzochten we in hoeverre deze in staat was te voorspellen in welke mate kinderen met dyslexie zouden profiteren van gespecialiseerde behandeling. In dat kader werd de dynamische test afgenomen bij kinderen die gediagnosticeerd waren met dyslexie en evalueerden wij hun lees- en spellingvaardigheid voor en na een periode van tien maanden van gespecialiseerde dyslexiebehandeling. De resultaten wezen uit dat de prestaties op de dynamische test significant bijdroegen aan het verklaren van variantie in leesvaardigheid bij de nameting (die niet verklaard kon worden door de voormeting) en dit bovendien beter deden dan traditionele statische leesgerelateerde maten, zoals fonologisch bewustzijn en snelheid van benoemen.

De resultaten van de eerste drie empirische studies gaven evidentie voor een fundamenteel verstoord vermogen van het leren van klank-tekenkoppelingen bij kinderen met dyslexie. Ondanks dat het door het gebruik van een artificieel schrift onwaarschijnlijk was dat onze bevindingen konden worden toegeschreven aan verschillen in leeservaring, konden we dit ook niet volledig uitsluiten. In de laatste studie (Hoofdstuk 6) gingen we daarom een stap verder en onderzochten het leren van klank-tekenkoppelingen bij kleuters. We namen onze dynamische test aan het eind van Groep 2 af bij kinderen met een verhoogd familiair risico op dyslexie en bij hun leeftijdgenoten zonder verhoogd risico. Het lezen van losse woorden werd twee jaar later, aan het eind van Groep 4, gemeten. De resultaten lieten zien dat de kinderen met een verhoogd risico op dyslexie minder goed presteerden op de dynamische test dan hun leeftijdgenoten zonder verhoogd risico. Ondanks dat de dynamische test werd afgenomen voor aanvang van het leesonderwijs, bleek deze de leesprestatie aan het eind van Groep 4 significant te voorspellen en op voorhand te kunnen identificeren welke kinderen later leesachterstanden zouden ontwikkelen. Onze data wees dus uit dat een verstoord vermogen om klank-tekenkoppelingen te leren een causale factor is in dyslexie en niet verklaard kan worden door verschillen in leeservaring.

Tezamen leveren onze bevindingen sterk bewijs voor de opvatting dat een verstoord vermogen om goed geïntegreerde klank-tekenkoppelingen te leren een sleutelfactor is in dyslexie en bieden zij verschillende aanknopingspunten voor concrete toepassingen in onderwijs en zorg.



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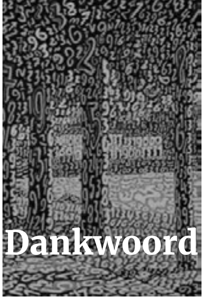

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