Why so fast?

An investigation of the cognitive and affective processes underlying successful and failing development of reading fluency

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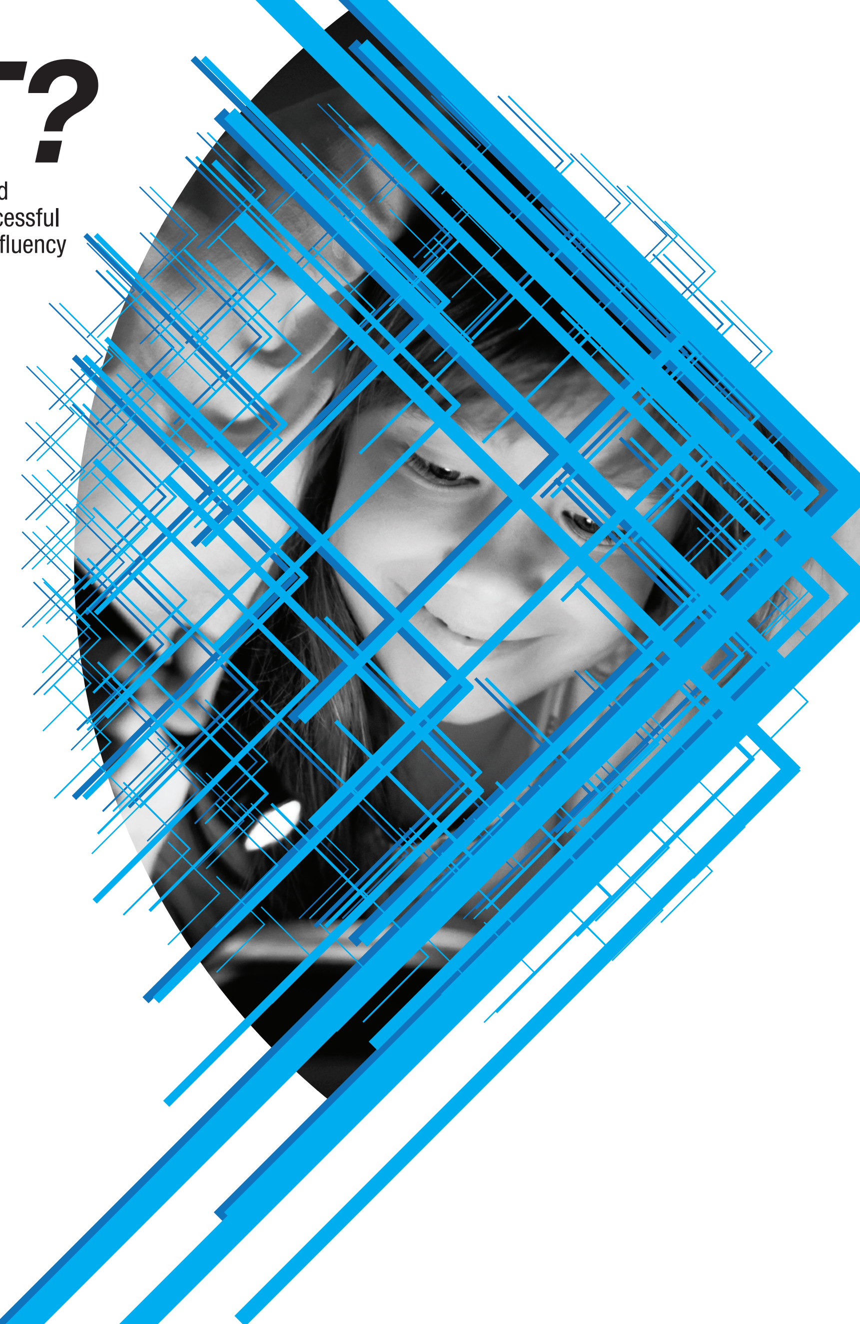

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Chapter 1

General introduction

You may not realize it, but the fact that you are able to read this thesis is actually a remarkable accomplishment. While we learn to speak automatically, learning to read requires explicit instruction. And in contrast to spoken language, which is as old as mankind, written language is a fairly recent cultural invention. It was developed only around 6000 years ago (Rayner & Pollatsek, 1989) and for centuries, the ability to read and write was a privilege of only a small percentage of the world population. Therefore, our brains have most likely not been evolutionarily equipped for the task of reading, but rather had to 'recycle' areas that were originally developed for other purposes when humans began to read (Dehaene, 2009; Dehaene, Cohen, Morais & Kolinsky, 2015). However, despite the absence of a specialized brain area for reading, most adults in western society are able to recognize written words quickly and seemingly automatically. In fact, the ability to read fluently has become essential for successful participation in modern society (National Reading Council, 1998; Snowling, 2000; Stichting Lezen en Schrijven, 2017). For example, road signs along the highway, subtitles on television and timed examinations in educational settings all require the quick and accurate interpretation of text.

This raises the question how beginning readers learn to become so fluent in the complex skill of reading for which their brain was not inherently adapted. This question is especially relevant for children with dyslexia, who are characterized by severe and persistent difficulties in achieving appropriate levels of reading fluency. Therefore, the studies presented in the current thesis aim to improve our understanding of the development of reading fluency in typical readers and children with dyslexia. Specifically, the studies focus on the cognitive and affective processes that underlie both successful and failing reading fluency. We are especially interested in fluent reading because, although decades of reading research has primarily addressed reading accuracy (Share, 2008), in transparent orthographies such as Dutch, reading accuracy approaches ceiling level after the first year of reading instruction (Seymour, Aro & Erskine, 2003). Accordingly, in a study of Dutch children in first to sixth grade, there was little room for improvement in reading accuracy after grade one, whereas reading fluency continued to ameliorate until grade six (Vaessen & Blomert, 2010). In addition, reading fluency problems are characteristic of children with dyslexia. They can be trained to achieve adequate reading accuracy, but often remain dysfluent (Thaler, Ebner, Wimmer & Landerl, 2004; Torgesen et al., 2001). In fact, dysfluency has been identified as the 'most notorious' or 'typical' problem of dyslexic readers in languages with transparent orthographies (Blomert, 2011; Wimmer & Mayringer, 2002). The studies in this thesis focus on reading at the word level. Word reading is assumed to be the 'hallmark of skilled reading' (Ehri, 2005), with word recognition skills distinguishing between individuals with poor and high overall reading ability (Perfetti, Goldman & Hogaboam, 1979) and constituting a crucial factor in reading comprehension (Gough & Turner, 1986). In addition, the reading disability of dyslexic readers is most pronounced during reading at the word level. That is, although dyslexic readers have been shown to experience difficulties with text level reading (e.g. Hutzler & Wimmer, 2004; Wimmer, 1993) and reading comprehension (Swanson & Alexander, 1998), they can use contextual cues to compensate for their decoding deficit during reading above the word level (Nation & Snowling, 2008). Word reading fluency thus seems to be at the heart of both typical reading development as well as the impairment of dyslexic readers.

Reading development

The foundation for reading development is formed long before the start of formal education, since reading skills build upon spoken language skills. That is, when children first learn to use spoken words to represent objects in their environment, they form word representations in memory. These word representations contain two components: a phonological representation, which represents the word's pronunciation, and a semantic representation identifying the meaning of the word. Initially, children's phonological representations are relatively global, and refer to whole words. However, throughout development, representations become increasingly specific and identify word parts, such as syllables, onsets, rhymes, and phonemes. This enables children to combine these word parts into whole words, and to identify which words rhyme or have identical onsets (Goswami, 2000). When children learn to read, a third component is added to the word representations. This is the orthographic representation, or the spelling of words.

Several theories have been influential in forming our knowledge of these orthographic representations and reading development. According to the phase-theory of Ehri (2005), the development of orthographic representations proceeds in four phases. During the initial, pre-alphabetic phase, children do not yet master orthography-phonology ('or grapheme-phoneme') relations, but recognize certain words on the basis of salient, visual features or contextual cue. This occurs for example when a child recognizes the word 'McDonalds' on the basis of the yellow M. When children learn the pronunciation of certain letters, they progress to the partial alphabetic phase. From this phase onwards, the alphabetic system is used to recognize words. Initially, children recognize words on the basis of some of its letters, such as identifying 'book' on the basis of the 'b' and 'k'. This results in numerous reading errors, since words with similar characters (e.g. 'bank' or 'black') are easily confused. Children become full alphabetic readers when they know most grapheme-phoneme connections. Now they can relate all letters in a word to their corresponding pronunciation, and use this decoding to access the phonological representation of the whole word. In the final, consolidated phase, orthographic representations become more specific. With increasing decoding experience, children learn to form grapheme-phoneme connections of larger units such as letter clusters, onsets, rimes, syllables or entire words. During reading, the phonological representations of these units can be retrieved as a whole, which speeds up reading fluency.

The self-teaching hypothesis (Share, 1995; 1999) describes how children, once they master the orthography-phonology connections, can use their decoding skills to establish orthographic representations of words in memory. That is, once a child encounters a new written word, this child can apply the available decoding skills to translate the letters into speech sounds and address the word's pronunciation. If the child already knows the spoken form of the word, both phonological and semantic word representations are present in memory. The child can now add the orthographic form of the word to these phonological and semantic representations and store it in memory for use in future reading activities. In this way, every successfully decoded word provides the child with an opportunity to set up direct connections between written and spoken word forms and thus, builds an orthographic lexicon.

Although the single first encounter of a written word can already result in the formation of an orthographic representation of this word, the lexical quality hypothesis (Perfetti, 2007; Perfetti & Hart, 2002) describes how the quality of this representation continues to ameliorate when words are read more often. Representations of high lexical quality are precise (to allow distinguishing between similar words, such as 'hair' and 'heir') as well as flexible (to recognize that 'fast' and 'quick' have the same meaning). In addition, these representations encompass close connections between the orthographic, phonological and semantic components. High quality representations can be retrieved more efficiently, which manifests in fluent word recognition. The vocabulary of an individual reader contains representations of varying levels of quality, ranging from low quality representations for words that have rarely been encountered, to high quality representations for high frequent words. In addition, a given word can be of high quality in one person's lexicon, but of much lower quality in the lexicon of another person, if this person has read this word less often.

According to dual-route theories of reading (e.g. Coltheart, Curtis, Atkins & Hailer, 1993; Coltheart, Rastle, Perry, Langdon & Ziegler 2001; Perry, Ziegler & Zorzi, 2007), the quality of an orthographic representation influences the process involved in recognizing this word in text. Dual route theories distinguish two different routes to word recognition. In the sublexical route, words are decoded letter by letter, through the application of phoneme grapheme conversion rules. In the lexical route, in contrast, the word is identified as a whole, by direct activation of its representation in memory. During reading, both routes are activated simultaneously. The sub-lexical route is relatively slow and effortful, but effective for decoding new words or nonwords for which no, or only low quality, orthographic representations exist. The lexical route is efficient for the quick recognition of familiar words. During reading development, most readers experience a gradual shift in word recognition strategy, from predominant use of the sub-lexical route during the first stages of reading acquisition, to quick, lexical word recognition when many words are represented in the orthographic lexicon. That is, during Ehri's full alphabetic phase, children are dependent on decoding through the sublexical route. However, in the consolidated phase, children become increasingly able to decode at the word level, build orthographic representations of successfully decoded words and ameliorate the quality of these representations after repeated encounters. As the number and quality of orthographic representations in the children's lexicons grows, the lexical route becomes increasingly effective and thereby preferable above the sub-lexical route.

Orthography-phonology integration

As becomes clear from all theories mentioned above, the formation of connective bonds between the orthographic and phonological representations of letters and words constitutes an important component of reading skill. Accordingly, knowledge of the relation between letters and speech sounds is strongly related to reading development in readers of various alphabetic orthographies (Foulin, 2005). In addition, neural correlates of orthography-phonology integration are related to reading fluency (Blau, van Atteveldt, Ekkebus, Goebel & Blomert, 2009; Blau et al., 2010) and computational models of word reading, which are driven to a large extent by phoneme-grapheme conversion rules, have been able to simulate various characteristics of the human reading process, both related to skilled reading (Coltheart, 2005; Coltheart et al., 2001; Ziegler, Perry & Coltheart, 2000), and learning to read (Plaut, McClelland, Seidenberg & Patterson, 1996; Seidenberg & McClelland, 1989).

The ease with which children acquire orthography-phonology connections depends on their language's orthographic depth, i.e. the regularity with which the spoken language is represented in written language (Seymour et al., 2003). In languages with relatively shallow (or 'transparent') orthographies, such as Italian, Finnish, German and Dutch, a letter is generally pronounced the same across words. In contrast, in languages with deep (or 'opaque') orthographies such as English, French and Danish, the same letter can be pronounced differently across words (e.g. the 'o' in rock, no, down, love, lose, cough). In transparent orthographies, most children acquire orthography-phonology correspondences within the first year of reading instruction (Blomert & Vaessen, 2009). However, it takes until adulthood before orthography-phonology connections become truly automatized (Blomert & Vaessen, 2009; Froyen, Bonte, van Atteveldt & Blomert, 2009), and become represented as stable integrated "graphoneme" objects (Whitney & Cornelissen, 2005). This suggests that, subsequent to the acquisition of accurate decoding skills, an important and long-lasting phase in the reading development process is related to the fine-tuning of the grapheme-phoneme connections into a fluent, rapid and flexible word recognition system. Evidence that orthography-phonology connections are highly automatized in skilled readers comes from studies showing that the orthographic representation of a word is activated automatically when this word is presented phonologically (Bruck, 1992; Castles, Holmes, Neath & Kinoshita, 2003; Landerl, Frith & Wimmer, 1996), just as phonological information is automatically activated on the basis of an orthographically presented word (Booth, Perfetti & MacWhinney, 1999; Ferrand & Grainger, 1992; Rastle & Brysbaert, 2006). In addition, visual letters appear to modulate a pre-attentive measure of speech sound processing, indicating that the letters and speech sounds had interacted automatically (Froyen et al., 2009).

An interesting series of studies has portrayed the time course of orthographic and phonological component processes during word recognition in skilled French readers (Ferrand & Grainger, 1992; 1993; 1994). These studies thus explicated at which point in time the visual letters of the written word activate its orthographic representation in memory, and subsequently translate this orthographic representation to the accompanying phonological representation in order to access word meaning. Results showed that, in readers of the opaque orthography French, orthographic codes are activated before 17 milliseconds, and are translated to phonological codes around 50 milliseconds. Activation of both orthography and phonology occurred during the first stage of the word recognition process. This activation proceeds without full awareness of the reader, thereby indicating that grapheme-phoneme connections could be formed automatically. These findings raise the question of how this automaticity in orthography-phonology connection is achieved, and thus how these time courses develop when children learn to become fluent readers. Moreover, Ferrand and Grainger investigated time courses in readers of the deep French orthography, and it is unclear whether similar time courses are present in Dutch readers.

It could be argued that the consistent orthography-phonology relations in the shallow Dutch orthography allow quicker activation of phonological representations once orthographic representations are accessed. In fact, the Orthographic Depth hypothesis (Frost, 1998; 2005) assumes that during the very first stages of the word recognition process, readers use an access representation of the word that is read. This access representation is as simple as possible while retaining relevant word information to allow identification of the correct word in the lexicon as quickly and unequivocally as possible. Readers of opaque orthographies are assumed to employ access representations with underspecified phonology, and to activate phonological codes later in the word recognition process. In contrast, readers of transparent orthographies can assemble phonology quickly, and thus use relatively detailed phonological information to access word representations (Frost, 1998; 2005). The Orthographic Depth hypothesis thus postulates that phonological influences affect the word recognition process earlier in transparent than in opaque orthographies. Therefore, the first aim of the present thesis is to investigate the time course of orthographic and phonological code activation in skilled Dutch readers. To this end we portray how orthographic representations are accessed and translated into phonological representations over time, once readers have established fully integrated, or automatized, orthography-phonology connections. This provides insight into the endpoint of the integration process of letters and speech sounds in Dutch readers. Once this endpoint is known, a second aim is to investigate how this integration process develops when children are learning to become fluent readers. Specifically, how do the connections between orthographic and phonological word representations become fine-tuned into fully integrated and quickly accessible graphoneme objects? To this end we study time courses of orthographic and phonological code activation in children at incremental levels of reading development.

Dyslexia

Although learning to read requires instruction and practice, most children develop fluent reading skills fairly easily. However, three to ten percent suffer from dyslexia and experience severe and persistent difficulties in acquiring appropriate reading skills, despite adequate education and intelligence (Snowling, 2013). The peculiarity and specificity of dyslexia was already noticed in the nineteenth century. In 1887, professor Rudolf Berlin first introduced the name 'Dyslexia' to describe cases of severe reading difficulties that occurred in the absence of visual or speech problems (Wagner, 1973). In 1896, the British physician W. Pringle Morgan described a 14 year old boy:

"He has always been a bright and intelligent boy, quick at games, and in no way inferior to others his age. His great difficulty has been—and is now—his inability to read. He has been at school or under tutors since he was 7 years old, and the greatest efforts have been made to teach him to read, but, in spite of this laborious and persistent training, he can only with difficulty spell out words of one syllable……I might add that the boy is bright and of average intelligence in conversation. His eyes are normal…and his eyesight is good. The schoolmaster who has taught him for some years says that he would be the smartest lad in the school if the instruction were entirely in oral." (Morgan, 1896, p. 1378).

Dyslexia is defined as a specific reading and spelling disability, with a neurobiological origin (Blomert, 2005). In today's literate society, the reading and spelling impairments render people with dyslexia vulnerable to academic, economic and psychosocial disadvantages (UNESCO, 2005). With specialized dyslexia treatment, dyslexic readers have been shown to achieve age appropriate levels of reading accuracy (Hatcher et al., 2006; Tijms, 2007). However, reading fluency often remains inefficient (Thaler et al., 2004; Torgesen et al., 2001).

The most prominent account of dyslexia assumes that the reading and spelling problems that characterize persons with dyslexia are caused by deficits in their phonological processing skills (Snowling, 1998; Vellutino, Fletcher, Snowling & Scanlon, 2004). According to this phonological deficit theory, people with dyslexia have a reduced ability to process the speech sounds that are represented in written words. This manifests in difficulties with deleting or substituting phonemes from words. As a consequence of this phonological deficit, people with dyslexia form less specific phonological representations of words, are less efficient in storing and retrieving words from memory and in integrating letters with speech sounds. Although the phonological deficit hypothesis is well-supported, the causal role of phonological processing skills in developmental dyslexia has been questioned. Questions arose when phonological skills were found to develop also as a consequence, and not only as a precursor of reading acquisition (Bishop, 2006; Boets et al., 2010; Mann & Wimmer, 2002, but see Molfese, 2000) and training of phonological skills did not result in enhanced reading development (Castles, Coltheart, Wilson, Valpied & Wedgewood, 2009). Moreover, some dyslexic children possess adequate phonological skills but are still severely dysfluent in reading (Biancarosa & Snow, 2004; Blomert, 2011).

Orthography-phonology integration in dyslexic readers

In contrast to the phonological deficit hypothesis, an alternative account of dyslexia suggests that an orthography-phonology integration deficit constitutes a proximal and core cause of dyslexia (Blomert, 2011; Hahn, Foxe & Molholm, 2014; Kronschnabel, Brem, Maurer & Brandeis, 2014). In this view, both the reading difficulties and phonological processing problems result from the impairments in forming efficient orthography-phonology connections. In accordance with the assumption of a core deficit of orthography-phonology integration, children at familial risk for dyslexia were shown to experience difficulties in the acquisition of orthography-phonology correspondences before the start of formal reading education (Blomert & Willems, 2010). Furthermore, dyslexic children appeared to have a reduced ability in recognizing mismatches between written and spoken (pseudo)words (Fox, 1994; Snowling, 1980), and were less fluent in letter-speech sound binding, after learning letter-speech sound connections in an artificial script (Aravena, Snellings, Tijms & van der Molen, 2013). The orthography-phonology integration deficit is assumed to primarily hamper the automatisation of orthography-phonology representations. That is, dyslexic children do succeed in the initial establishment of associations between orthography and phonology, but are impaired in the subsequent refinement of these associations into quickly accessible, or automatized, representations (Blomert, 2011; Blomert & Vaessen, 2009; Froyen, Willems & Blomert, 2011). Impairments in orthography-phonology integration are not only present in children (Moll, Hasko, Groth, Bartling & Schulte-Körne, 2016), but also in adolescents (Kronschnabel et al., 2014) and adults (Mittag, Thesleff, Laasonen & Kujula, 2013). This indicates that letters and speech sounds are still not fully integrated when dyslexic readers reach adulthood.

A possible explanation for the orthography-phonology integration deficit of dyslexic readers is offered by the asynchrony hypothesis (Breznitz, 2002; 2006; Breznitz & Misra, 2003). According to this hypothesis, visual-orthographic information and auditory-phonological information need to be processed in the same time-window in order to allow efficient integration. In all readers, processing speed differs between the visual and auditory domain, but in typical readers this difference is small enough to be bridged. However, dyslexic readers are characterized by delayed processing speed in both the visual and auditory domain. This results in a time gap between the activation of orthographic and auditory information, and hence information from one system may deteriorate before the complementary information from the second system is activated.

Previous research has supported the assumption of an increased delay in visual-auditory processing in dyslexic children (Snellings, van der Leij, de Jong & Blok, 2006). However, the exact nature of this delay is thus far unknown. Insight in the timing of the integration between orthographic and phonological representations during word reading in dyslexic children could enhance our understanding of the orthography-phonology integration deficit. In the current thesis we portray the timing of the orthography-phonology integration process in normal reading children. This can serve as a reference point for future studies that include children with dyslexia. Comparing the time courses of the orthography-phonology integration process between normal reading children and children with dyslexia allows identifying whether and at what point in time delays occur in dyslexic readers.

Feelings of uncertainty in children with dyslexia

An aspect of dyslexia that has received relatively little scientific attention is the emotional consequences of years of failure in reading and academic tasks. Children with dyslexia experience heightened levels of stress, worries, uncertainty and low self-esteem (Alexander-Passe, 2007; 2008; Ingesson, 2007). Their stress is primarily related to reading and academic tasks, but has also been shown to generalize to depression, generalized anxiety and post-traumatic stress symptoms (Alexander-Passe, 2015a; 2015b; McNulty, 2003). Academic problems and emotional problems are known to be mutually influential (Eccles, Wigfield & Schiefele, 1998). Therefore, it is well possible that although the emotional problems are initially the consequence of the failure in achieving adequate reading performances, in time the emotional problems may also exaggerate the reading difficulties. In support of this assumption, extensive worrying has been shown to delay information-processing speed (Eysenck, Derakhshan, Santos & Calvo, 2007).

Emotional factors of dyslexia are not strongly represented in current theories on dyslexia. However, the multiple deficit account proposes that dyslexia is a multifaceted and dimensional, rather than categorical, deficit. That is, in each individual, several dyslexia characteristic difficulties are assumed to range from non-existent, to mild, to severe. Accordingly, there is not one underlying cause of dyslexia, but several risk and protective factors that interact to impact literacy development and thus to render a person more or less vulnerable to develop dyslexia (Moll, Loff & Snowling, 2013; Pennington, 2006). As mentioned above, deficits in phonological processing skills and orthography-phonology integration are amongst these risk factors. Phonological processing deficits are often considered the core deficit, although the severity of these phonological problems differs across individuals, and the impact of the phonological problems on reading skills depends on the presence of additional risk and protective factors (Bishop & Snowling, 2004; Peterson, Pennington, Shriberg & Boada, 2009). Most of the potential risk factors studied are cognitive in nature, including deficits in rapid naming, verbal short-term memory, low-level visual and auditory skills and language skills (Moll et al., 2013; Pennington et al., 2012; Ramus et al., 2003). However, it is well possible that also affective factors contribute to the liability for developing dyslexia. Therefore, the third aim of the current thesis is to study the impact of feelings of uncertainty, in addition to the impact of phonological processing skills, to the dysfluent word reading of children with dyslexia. We aim to elucidate whether uncertainty aggravates the impact of the phonological difficulties on reading fluency in children with dyslexia.

Dyslexia and learning to read in a foreign orthography

In The Netherlands, once children have learned to read in their native orthography, they start acquiring reading skills in foreign orthographies. Mastering literacy in multiple languages is highly beneficial in the current international society. However, this entails that dyslexic students face the challenge of learning to read in a new orthography. According to the Linguistic Coding Differences Hypothesis (Sparks & Ganschow, 1991), reading development in the orthography of the foreign language is related to reading proficiency in the orthography of the native language. That is, successful acquisition of reading skills in the foreign orthography is founded upon phonological, orthographic and syntactic skills in the native orthography. Consequently, dyslexics' poor phonological processing skills in the native language result in difficulties when learning to read in a foreign language (Ganschow, Sparks & Schmeider, 1995). This suggests that the extent to which dyslexic children experience reading difficulties in a foreign orthography depends on the importance of phonological processing for learning to read in the orthography involved. Specifically, learning to read may be easier in some foreign orthographies than in others for children with dyslexia.

However, it is currently unknown to what extent the underlying skills involved in reading acquisition in a foreign orthography are influenced by characteristics of the specific orthography. It has been suggested that although some cognitive skills that underlie reading are universal, the degree to which other skills are involved differs amongst orthographies (Geva & Siegel, 2000; Koda, 2007; Perfetti, Cao & Booth, 2013). It might therefore be the case that skills that are essential for reading development in one foreign orthography are less involved in reading acquisition in another orthography. Insight in the cognitive skills that underlie reading fluency in languages with contrasting orthographic characteristics may inform us about the degree to which these skills are universal or language specific. This insight in correlates of foreign language reading development in general, may then subsequently serve as a basis to explore how children with dyslexia learn to read in different foreign languages.

Research on foreign literacy acquisition has predominantly focussed on individuals who learn to read in a foreign alphabetic orthography, i.e. in an orthography that uses the alphabet to represent spoken language in written form. For example, native speakers of Spanish or Chinese who learn to read in English (Bialystok, Luk & Kwan, 2005; Chow, McBride-Chang & Burgess, 2005; Durgunoglu, Nagy & Hancin-Bhatt, 1993; Gottardo, Yan, Siegel & Wade-Woolley, 2001; Lindsey, Manis & Bailey, 2003; Pan et al., 2011; Wang, Perfetti, & Liu, 2005), or English speaking children in French immersion programs (Deacon, Commissaire, Chen & Pasquarella, 2013; Genesee, & Jared, 2008). However, far less is known about the acquisition of reading skills in orthographies with other writing systems. The Chinese writing system for example, uses characters that are visually far more complex than the letters of the alphabet and do not represent phonemes as directly as letters. Consequently, researchers who study Chinese children who learn to read in their native language have wondered whether learning to read in Chinese may rely less on phonological processing skills than learning to read in alphabetic orthographies (Huang & Hanley, 1997; McBride-Chang & Kail, 2002; Siok & Fletcher, 2001). Other skills, most notably visual and morphological skills, may be more important (McBride-Chang, Shu, Zhou, Wat & Wagner, 2003; Yeung et al., 2011).

However, research has not yet focussed on the cognitive skills that underlie Chinese reading development in native speakers of a language with an alphabetic orthography. Therefore, it is unknown whether the same skills that contribute to reading development in Dutch are also involved when Dutch children learn to read in Chinese. Therefore, the fourth aim of the current thesis is to identify which cognitive skills are involved when skilled readers of Dutch develop reading fluency in the nonalphabetic Chinese orthography. We also aim to establish to what extent these skills are similar or different from the skills that are involved in reading acquisition in the foreign alphabetic orthographies Spanish and French. By studying reading fluency development in the nonalphabetic orthography Chinese, the transparent alphabetic orthography Spanish and the opaque alphabetic orthography French, we can investigate the impact of writing system as well as orthographic depth on foreign language reading acquisition. This will clarify to what extent the skills that underlie reading development in a foreign language are universal or language specific.

The current thesis

The aim of the current thesis is to enhance our insight into the development of reading fluency in typical readers and children with dyslexia. To this end, we conducted four studies that investigate the cognitive and affective mechanisms that underlie both successful and failing reading fluency development.

The first two chapters focus on the formation of orthography-phonology connections that underlie word reading fluency. Specifically, these chapters aim to elucidate at what point in time orthographic codes are activated during the encounter of a visual word, and how quickly these orthographic codes are translated into phonological codes in order to access word meaning. In **chapter two**, these time courses of orthographic and phonological code activation are investigated in skilled adult readers of the Dutch orthography. The goal of this chapter is twofold. First, the time courses in skilled readers of the transparent Dutch orthography can be compared with the time courses of skilled readers of the opaque French orthography that were identified in previous research (Ferrand & Grainger, 1992; 1993; 1994). This will clarify to what extent the timing of the activation of orthographic and phonological representations during word reading is influenced by the orthographic depth of the orthography that is being read. Second, the time courses in highly proficient adult readers identify how letters and speech sounds are connected in Dutch readers that have fully automatized orthography-phonology connections. These can then subsequently be used as a reference point to investigate how the automatization of these orthography-phonology connections develops when children learn to become fluent readers of the Dutch orthography.

In **chapter three**, we portray time courses of orthographic and phonological code activation in Dutch children at incremental levels of reading development. We study children in grades 2, 4 and 6 since this assumedly covers the period in education in which grapheme-phoneme correspondences are already acquired, but the automatization of these correspondences is still developing. We aim to elucidate how the timing of access to orthographic representations and the subsequent coupling to phonological representations develops when children become more fluent in reading.

In chapter four and five, we no longer focus specifically on orthography-phonology integration, but on other cognitive and affective processes that are important for reading fluency. **Chapter four** investigates the effects of underlying phonological processing skills and uncertainty on word recognition fluency in 4th grade typical and dyslexic readers. The role of phonological processing deficits in dyslexics' word reading problems is well documented (Snowling, 1998; Vellutino et al., 2004). However, it is unknown to what extent the impact of these phonological deficits is aggravated by emotional problems that dyslexic children experience, such as uncertainty about their reading skills. In addition, it is debated whether dyslexics' phonological problems also impair their word recognition skills in the auditory domain (Bradlow, Kraus & Hayes, 2003; Dole, Hoen & Meunier, 2012; Ramus, White & Frith, 2006; Rosen, 2003; Ziegler, Pech-Georgel, George & Lorenzi, 2009). Therefore, we study the role of phonological processing skills and uncertainty in visual word recognition (word reading) as well as in auditory word recognition.

Finally, in **chapter five**, our focus shifts to reading fluency development in a foreign language. That is, once Dutch children have acquired fluent reading skills in their native language, they are generally introduced to one or more foreign languages and have to start acquiring reading fluency all over again. Increasingly often, children do not acquire just one, but multiple foreign orthographies. In recent years, some schools have moved beyond teaching foreign alphabetic orthographies, and now also teach languages with a nonalphabetic writing system such as Chinese. However, little is known about the underlying cognitive skills that are involved when native Dutch readers learn to read in a foreign orthography. Specifically, it is unclear whether the same skills that are involved in reading development in the native Dutch orthography contribute to reading acquisition in a foreign orthography as well, and to what extent the influence of different underlying skills is similar or different for different foreign orthographies. It could be argued that the writing system and orthographic depth of a foreign orthography influence the degree to which different underlying cognitive skills are involved. Therefore, chapter five studies adolescents who are fluent readers of Dutch and learn to read simultaneously in three foreign orthographies: the transparent alphabetic Spanish orthography, the opaque alphabetic French orthography and the nonalphabetic Chinese orthography. This knowledge about the contribution of cognitive skills to foreign language reading development in typical readers may serve as a basis for future studies to identify how foreign language reading development in children with dyslexia is influenced by characteristics of the language involved.

Together, the studies in the current thesis aim to increase our knowledge of the cognitive and affective factors that underlie the development of reading fluency. To this end we study readers at different stages of reading fluency development, typical readers as well as children with dyslexia, and reading fluency in the native language as well as in foreign languages. Results of all studies will be summarized, integrated where possible and interpreted in terms of both scientific and societal implications in a general discussion described in **chapter six**.

Chapter 2

Time course analyses of orthographic and phonological priming effects during word recognition in a transparent orthography

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Abstract

In opaque orthographies, the activation of orthographic and phonological codes follow distinct time courses during visual word recognition. However, it is unclear how orthography and phonology are accessed in more transparent orthographies. Therefore, we conducted time course analyses of masked priming effects in the transparent Dutch orthography. The first study used targets with small phonological differences between phonological and orthographic primes, which are typical in transparent orthographies. Results showed consistent orthographic priming effects, yet phonological priming effects were absent. The second study explicitly manipulated the strength of the phonological difference and revealed that both orthographic and phonological priming effects became identifiable when phonological differences were strong enough. This suggests that, similar to opaque orthographies, strong phonological differences are a prerequisite to separate orthographic and phonological priming effects in transparent orthographies. Orthographic and phonological priming appeared to follow distinct time courses, with orthographic codes being quickly translated into phonological codes and phonology dominating the remainder of the lexical access phase.

Introduction

Although it is now well established that both orthography and phonology play a crucial role in visual word recognition, the interrelationship and time course of orthographic and phonological processes are still subject to debate. Key questions are whether they operate independently from each other, whether they are performed sequentially or in parallel, and whether they are automatic or strategic (Braun, Hutzler, Ziegler, Dambacher & Jacobs, 2009; Rastle, 2007). In order to answer these questions, research has focused on the earliest stages of the reading process in which orthography and phonology are accessed (Ziegler, Grainger & Brysbaert, 2010). Since this access stage evolves highly rapid and seemingly effortless in skilled readers, a paradigm is required that allows for the assessment of very fast processes. The masked priming technique (Kinoshita & Lupker, 2003) meets this requirement. In particular, time course analysis of masked priming effects has proven to be highly informative. With this technique Ferrand and Grainger (1992, 1993, 1994) showed that, in French proficient readers, orthographic and phonological code activation follow distinct time courses, where activation of orthographic codes precedes activation of phonological codes.

Orthographies around the world show remarkable differences with respect to the consistency between the speech sounds in oral language and the written forms that represent these speech sounds in print (Protopapas & Vlahou, 2009). Therefore, the question arises whether theories and models on word recognition that apply in one language can explain phenomena in another language as well (e.g. Bick, Goelman & Frost, 2011, Durgunoğlu & Öney, 1999; Goswami, Gombert & Fraca de Barrera, 1998; Ziegler, Perry & Coltheart, 2000; Ziegler, Perry, Jacobs & Braun, 2001). For example, time course analyses of masked priming effects have repeatedly been conducted in French (Ferrand & Grainger, 1992; 1993). However, French has a semi-opaque orthography, with inconsistent relations between orthography and phonology. It is unclear whether the activation of orthographic and phonological codes follow similar time courses in more transparent orthographies, with consistent letter-speech sound relations. Therefore, the aim of the current study is to examine the time courses of orthographic and phonological code activation in a transparent orthography such as Dutch.

Orthographic consistency effects on lexical access

In relatively transparent orthographies, such as Italian, Finnish, German and Dutch, consistency is large, which entails that across words, a certain letter is generally pronounced identically. Conversely, in more opaque orthographies such as English, Danish and French, a similar letter can be pronounced differently (e.g. the o in rock, no, down, love, lose, cough). It is now well known that this (in)consistency influences the rate of reading development (Seymour, Aro & Erskine, 2003). However, less is known about the effects of orthographic (in)consistency on the processes that underlie visual word recognition. The Orthographic Depth hypothesis (Frost, 2005; Katz & Feldman, 1983; Katz & Frost, 1992) proposes that orthographic consistency influences the processing style adopted in reading. It suggests that in transparent orthographies the consistent letter-sound relations encourage a phonological encoding style, where letters and small letter clusters are translated to their corresponding phonological units, and the word's meaning is derived from the assembled whole word phonological representation. In opaque orthographies on the other hand, the unreliable letter-sound relations render phonological encoding susceptible to errors. Consequently, lexical access relies more strongly on orthographic structure, with access to the whole word's phonology and corresponding meaning directly addressed on the basis of larger orthographical units.

Interestingly, the Orthographic Depth hypothesis postulates that orthographic consistency already exerts an effect during the earliest stage of the word recognition process. During this lexical access stage, the encoded visual word stimulus makes the first contact with the lexical information stored in the lexicon. In order to allow a rapid initial search through the lexicon, lexical access is based on an access representation that constitutes a simplification of the comprehensive representation in the lexicon, yet addresses the relevant lexical information of this representation as unequivocally as possible. In opaque orthographies, the inconsistent relations between graphemes and phonemes preclude quick phonological computation and result in an access representation that is underspecified or 'impoverished' with respect to phonology. More detailed phonological recoding occurs later in the word recognition process in opaque orthographies. However, in more transparent orthographies, phonology can be assembled quickly and thus allows lexical access to be based on a relatively detailed phonological representation (Frost, 1998; 2005). Therefore, on the basis of the Orthographic Depth hypothesis, phonological influences are expected to affect the word recognition process earlier in transparent than opaque orthographies. In the current study we will investigate this premise of the Orthographic Depth hypothesis.

Time course analyses of masked priming effects

Masked priming is a technique that is highly suitable to study early stages of the word recognition process (Forster & Davis, 1984). During the last decades, masked priming has offered valuable insights with respect to lexical access codes (Perea & Lupker, 2003) and the contributions of different component processes, most prominently phonology, orthography and morphology (Johnston & Castles, 2003; Frost, Forster & Deutsch, 1997). The technique has also been used successfully to study the development of word recognition (Castles, Davis, Cavalot & Forster, 2007) and the acquisition of a second language or script (Brysbaert 2003; Dimitropoulou, Duñabeitia & Carreiras, 2011a). Masked priming involves the presentation of a target word, which is preceded by a briefly presented and masked prime word. Numerous studies established that recognition of the target word can be facilitated if the prime shares characteristics with the target (see Kinoshita & Lupker, 2003). It is generally assumed that the overlapping features between prime and target allow the word recognition process to start at perception of the prime, thus resulting in a time advantage at the moment the target is perceived (Forster, Mohan & Hector, 2003). Through manipulation of the type and degree of overlap between prime and target, it is possible to examine which component processes are involved in the word recognition process. The masked priming paradigm offers two particular advantages. First, since primes can be presented very briefly, their effects provide insight in the earliest stages of word processing. Second, the brief presentation duration prevents fully conscious processing of the prime, and thereby limits strategic effects (Forster, Mohan & Hector, 2003).

In time course analyses of masked priming effects, the exposure duration of primes is manipulated in order to examine when orthographic and phonological information become available during visual word recognition. Time course analyses of masked priming effects were first conducted in a series of lexical decision tasks (Ferrand & Grainger, 1992; 1993; for a slightly different paradigm, Ferrand & Grainger, 1994), in which target words were preceded by three nonword primes: 1) a phonological prime, which was pronounced identical, yet spelled slightly different than the target (a so called pseudohomophone, e.g. *lont* - *LONG*), 2) an orthographic prime, which shared the same degree of orthographic overlap with the target as the phonological prime, but was not a pseudohomophone (e.g. *lonc* – *LONG*), and 3) a control prime, which shared neither orthography nor phonology with the target (e.g. *tabe* – *LONG*). Faster recognition of a target that was preceded by an orthographic prime in comparison to a control prime was referred to as orthographic priming, and indicated that the orthographic overlap between prime and target had facilitated target recognition. Phonological priming was defined as the difference in recognition rate in the phonological as compared to the orthographic prime condition. Since both orthographic and phonological primes share the same degree of orthographic overlap with the target, any additional facilitation by the phonological prime should result from shared phonology.

Ferrand and Grainger (1992; 1993) showed that, in French, both orthographic and phonological priming effects resembled a reversed-U shaped time course pattern, yet emerged at different stages of the word recognition process. The facilitative effect of orthographic primes appeared between 17 and 50 ms and declined rapidly after 67 ms whereas phonological priming started to emerge between 50 and 67 ms and continued to exert a facilitative effect at priming durations as long as 100 ms. This indicates that, in French, orthographic and phonological processing follow distinct time courses, with orthographic activation preceding phonological activation.

At this point it should be noted that orthographic primes share not only orthographic, but also some degree of phonological overlap with the target (e.g. '*lonc*' shares three phonemes with '*LONG*'). Consequently, phonological influences may affect priming effects that are assumed to be purely orthographic in nature (Ferrand & Grainger, 1994). However, researchers have employed the opaqueness of the French orthography to orthogonally manipulate orthographic and phonological overlap (Ferrand & Grainger, 1994). This approach showed time courses largely similar to those found in the original design. These studies were all conducted in French, a semi-opaque orthography. Studies in the highly opaque English (Grainger, Kiyonaga & Holcomb, 2006) and logographic Chinese (Perfetti & Tan, 1998) orthographies report similarly patterned time courses. However, time courses in transparent orthographies have been less well delineated.

Masked priming effects in transparent orthographies

The few studies that did involve transparent orthographies, suggest that although orthographic priming effects are quite robust, phonological priming effects can only be observed if specific requirements are met. Two studies in the transparent Dutch orthography found orthographic priming, but no phonological priming, in a backward masked priming paradigm and in a forward masked priming paradigm with a prime exposure duration of 29 ms (Brysbaert, 2001-experiment 1; Brysbaert & Praet, 1992). In contrast, both orthographic and phonological priming effects could be established in a forward masked priming paradigm with a prime exposure duration of 43 ms (Brysbaert, 2001-experiments 2 and 3). Orthographic and phonological time courses mimicked those in a more opaque orthography, with the activation of phonological codes lagging behind the activation of orthographic codes. However, both studies adopted a perceptual identification task, which has been argued to be sensitive to strategic control (Perry & Ziegler, 2002), and therefore it is difficult to compare these results to the lexical decision results of Ferrand and Grainger. In addition, since only two prime exposure durations were used, time course analyses could not be done, which impeded insight in the buildup of phonological and orthographical codes over time.

To our knowledge, the only study that adopted time course analyses of masked priming effects in a transparent orthography was conducted by Carreiras, Perea, Vergara and Pollatsek (2009). These authors compared their event-related potential (ERP) measures in Spanish with an ERP-study in English (Grainger et al., 2006), and concluded that in both orthographies orthographic and phonological code activation show distinct time courses, with orthography being activated slightly before phonology. However, in contrast to expectations based on the Orthographic Depth hypothesis, phonological priming effects emerged *later* in the transparent Spanish orthography than in the opaque English orthography. However, interpretation of these findings is complicated by the fact that ERP findings were not corroborated by behavioural results, either because the task at hand did not involve behavioural responses (Grainger et al., 2006), or because the behavioural results did not reveal priming effects (Carreiras et al., 2009). In addition, important differences in task design impede straightforward comparisons between the two studies. Most notably, Grainger et al. used a semantic categorization task with both a forward and backward mask, and their stimuli contained large variations in the degree and place of overlap between prime and target words. Carreiras et al., on the other hand, used a lexical decision task with a forward mask only and their manipulation always involved the same letter (always the 'c') at the initial position in a word. Possibly, the restricted range of manipulations rendered the behavioural results insignificant (See Frost, Ahissar, Gotesman & Tayeb, 2003, page 350 for a similar argument).

In sum, current evidence about the time courses of orthographic and phonological priming effects in transparent orthographies is still inconclusive. Therefore, in Study 1 we aimed to obtain more decisive data regarding time courses of orthographic and phonological code activation in transparent orthographies. To this end we used a lexical decision paradigm similar to Ferrand and Grainger (1992; 1993), we carefully selected stimuli to assure variety in degree and place of overlap between prime and target words, and we systematically varied prime duration.

Study 1

Method

Participants

Of the 114 participants, 105 undergraduate and graduate students (63.8% female, mean age 20.62 years SD= 2.80) met the inclusion criteria of being a native Dutch speaker with normal or corrected to normal vision, absence of any form of neurological disability, and an average or above average (≥ Z-1) level of word recognition ability as measured with the One minute test of reading (*Een Minuut Test,* Brus & Voeten, 1979) and the Klepel pseudoword reading test (van den Bos, Lutje Spelberg, Scheepstra & de Vries, 1994). One participant only took part in two conditions (33 ms and 50 ms) due to technical defects. Participants received either course credit or a monetary reward for participation.

Materials and Design

The target stimuli were 90 words with lengths of 4, 5 or 6 letters. The targets were selected so as to allow for the generation of three types of pronounceable nonword primes: 1) a phonological prime, which was a pseudohomophone of the target (e.g. the prime *vrient,* pronounced as /vrint/, for the target *VRIEND* [friend], also pronounced as /vrint/), 2) an orthographic prime with the same number of shared letters with the target as the phonological prime, but not homophonic (e.g. *vrienk* (/vrink/) – *VRIEND (* /vrint/)) and 3) a control prime that had no letters in common with the target (e.g. *claumf* (/klɔumf/) – *VRIEND(* /vrint/)). The three primes related to a particular target were matched in number of letters, phonemes and syllables. In addition, the three primes did not differ in number of orthographic neighbours. For the purpose of the lexical decision task, 90 additional nonwords were generated to serve as foil targets. Each foil target was created by changing one or two letters of a word target. Consonants were replaced by consonants and vowels by vowels (e.g. *SPIEND* (/spint/) – *spient* (/spint/) – *spienk* (/spink/) – *draalm* (/draləm/). As a result of this procedure target words and foil nonwords were matched in number of letters, phonemes, syllables, and consonant-vowel structure. The foil nonwords did not differ significantly from the words in mean bigram frequency, number of neighbours and frequency of the highest frequent neighbour. In a similar way as described for the target words, for each target foil three different nonword primes were generated, a phonological prime, an orthographic prime and a control prime. All stimuli were selected with use of the wordgen application (Duyck, Desmet, Verbeke & Brysbaert, 2004) for the Celex database (Baayen, Piepenbrock & van Rijn, 1993). In the supplemental material, an overview of the stimulus set is provided in Table S1, and an overview of the lexical characteristics of the stimulus set can be found in Table S2. Three different experimental lists were created using these stimuli. Each of the 90 target words (and similarly each of the 90 target foils) was presented in all three lists, but was associated with a different prime type in every list. This ensured that each target word was presented once in each list, and that across lists, each target appeared in each priming condition. For example, the target *VRIEND* was primed with the phonological prime *vrient* in List 1, with the orthographic prime *vrienk* in List 2 and with the control prime *claumf* in List 3. The three lists did not differ with respect to mean bigram frequency, number of neighbours and frequency of the highest frequent neighbor, neither for the primes of the word targets nor for the primes of the foil targets. Priming conditions were rotated semi-randomly across lists, ensuring that each list contained an equal number of phonological, orthographic and control primes (30 items from each priming category). For each list, the 90 words and 90 nonwords were randomly divided into six subsets of 15 words and 15 nonwords. The content and ordering of subsets was held constant across lists. Each nonword was presented in a different subset than the word it was derived from, so that no subset contained both a word and its derivate nonword. Within every subset, words and nonwords had equal numbers of items from each word-length category and items were presented in randomized order.

Four different prime exposure durations were used: 33, 50, 67 and 83 ms. We selected identical exposure durations as Ferrand and Grainger (1993) to enhance comparison of phonological priming effects in the transparent Dutch and the opaque French orthography. Each participant was presented with all four exposure duration conditions in randomized order, and received the same experimental list with 180 target stimuli in all four exposure durations, yielding a total of 720 items.

Procedure

The primed lexical decision task was programmed in Presentation, and was presented using one of six identical 15- inch Acer Travelmate 4150 laptops. Stimuli appeared on the screen in a 16-point Courier font, in black letters against a white background. Letters were 4 mm in length and were presented in uppercase. Participants were seated at a viewing distance of 40-60 cm. The task started with six practice trials, divided into two blocks. During these practice blocks a well-trained test assistant could check understanding and repeat instructions if necessary. The practice trials included three word targets and three nonword targets that were not included in the experiment.

Every trial consisted of the following sequence of stimuli: 1) a forward mask consisting of a row of six hash marks (800 ms), 2) the prime, presented in lower case letters for one of the four prime exposure durations (33, 50, 67 or 83 ms), and 3) the target, presented in upper case letters. All stimuli were presented in the same location of the computer screen. The target remained on the screen until the participant responded, with a maximum response duration of 10 seconds. Participants were instructed to respond as quickly and accurately as possible. They responded by pressing one of two pre-allocated green and red coloured buttons on the keyboard. The colours were counterbalanced in order to compensate for possible handedness-effects or colour associations. Participants received no feedback on the accuracy of their responses.

The primed lexical decision task was preceded by a short word recognition task, which aimed to familiarize the participants with the target stimuli in order to reduce learning effects in response to the repeated presentation of the target stimuli during the lexical decision task. In this recognition task all 180 target stimuli of the lexical decision task (both words and nonwords) were presented in 20 blocks of nine items. All target stimuli were presented in black letters on a white background, with 800 ms presentation duration and a font, size and placement similar to the primed lexical decision task. Stimuli were divided across blocks in semi-randomized order, with each block including either four words and five nonwords, or five words and four nonwords. The order of stimulus presentation in the recognition task was unrelated to the presentation order in the primed lexical decision task. After each block, one (pseudo)word was presented in red letters, and the task of the participants was to decide whether this (pseudo)word had been presented amongst the nine preceding stimuli or not. Participants were encouraged to respond as accurately as possible and did not receive feedback on their response accuracy.

Results

Data cleaning

We included only targets that were familiar to all participants. Targets with a mean accuracy below 0.8 were excluded from further analyses. This led to the exclusion of three targets[1]. Removal of these items left matching of word and nonword targets on number of letters, phonemes, syllables, mean bigram frequency, number of neighbours and frequency of the highest frequent neighbor intact (for an overview of stimulus characteristics of the included items see Table 2 in the supplemental material). Only the reaction times of correct responses to word targets were analyzed (94.5% of the data for word targets). Premature responses were excluded by the removal of all responses below 250 ms (0.2 % of the correct responses to word targets). For each participant and condition, responses exceeding two standard deviations above the mean reaction time were excluded (4.7 % of the correct responses to word targets).

To make sure that response latencies were not affected by speed/ accuracy trade-offs, we calculated correlations between median RT of the correct responses and mean accuracy rates for each of the twelve prime type (phonological, orthographic and control prime) x prime exposure duration (33, 50, 67 and 83 ms) conditions. Correlations were all negative (ranging between -.32 and -.63) and significant. This indicates that, in each condition, targets that were responded to faster, were also recognized more correctly and thus speaks against the presence of speed-accuracy tradeoffs. As shown in Table 1, error percentages ranged between 4.5 and 6.4 across conditions, indicating that accuracy differences were small. Error

[1] These targets were the word target 'lijn' meaning "line", and nonword targets 'zwacht' en 'belijk'.

percentages were not considered further, all response latency analyses are based on correct responses only.

Orthographic and phonological priming effects

Median target word recognition latencies for the different prime type and exposure duration conditions are presented in Table 1. The data were analysed with a subject and item-level repeated measures ANOVA on median response latencies in which prime type and prime exposure duration were the main within factors, and list (list 1, 2 and 3) was the between factor. List was included as a dummy variable to extract variance due to the counterbalancing lists of the analyses (Pollatsek & Well, 1995). Results are reported for the subject-level (F_1) and item-level (F_2) separately. Analyses showed a main effect of prime type (F_1(1.92, 192.20) = 89.73, p < .001; F_2(2, 166) = 57.76, p < .001), a main effect of exposure duration (F_1(2.89, 289.40) = 11.35, p < .001; F_2(2.88, 239.16) = 46.70, p < .001) and an interaction effect (F_1(5.78, 578.21) = 7.90, p < .001; F_2(6, 498) = 9.37, p < .001). Consecutively, repeated measures ANOVA's were performed for each of the four prime exposure durations separately, to identify the time courses of orthographic and phonological priming effects. In each of these analyses, prime type was the main within factor and list was included as dummy variable. At 33 ms, the main effect of prime type approached significance in the subject level analyses, yet was non-significant at the item level (F_1(2, 200) = 2.64, p = .074; F_2(2, 166) = 0.92, p = .400). At the longer prime exposure durations the main effect of prime type was significant (50 ms: F_1(2, 200) = 27.44, p < .001; F_2(2.00, 166.00) = 28.46, p < .001, 67 ms: F_1(2, 202) = 42.13, p < .001; F_2(2, 166) = 40.41, p < .001, 83 ms: F_1(2, 202) = 48.91, p < .001; F_2(2, 166) = 36.57, p < .001).

At each presentation duration, the orthographic priming effect was operationalized as the difference in median RT between the orthographic and control primed conditions. Phonological priming was defined as the difference in median RT between the phonological and orthographic primed conditions. These planned comparisons indicated that at 33 ms, the orthographic priming effect showed a trend towards significance at the subject level, but was nonsignificant at the item level (F_1(1, 100) = 1.73, p = .096; F_2(1, 83) = 0.38, p = .270). From 50 ms onwards, the orthographic priming effect was clearly significant (50 ms F_1(1, 100) = 36.43, p < .001; F_2(1, 83) = 44.21, p < .001, 67 ms: F_1(1, 101) = 63.53, p < .001; F_2(1, 83) = 68.73, p < .001, 83 ms: F_1(1, 101) = 66.42, p < .001; F_2(1, 83) = 59.40, p < .001). The phonological priming effect on the other hand, was not significant at any of the four prime exposure durations (33 ms: F_1(1, 100) = 1.02, p = .158; F_2(1, 83) = 0.53, p = .235, 50 ms: F_1(1, 100) = 0.00, p = .496; F_2(1, 83) = 0.19, p =.332, 67 ms: F_1(1, 101) = 0.08, p = .389; F_2(1, 83) = 1.52, p =.111, 83 ms: F_1(1, 101) = 0.34, p = .282; F_2(1, 83) = 0.01, p =.453).

Table 1
Median target word recognition latencies in ms and error percentages (in parentheses) as a function of prime type and prime exposure duration in Study 1

	Phonological prime vrient - VRIEND	Orthographic prime vrienk - VRIEND	Control prime claumf - VRIEND	Orthographic priming effect	Phonological priming effect
33 ms	524 (4.5)	527 (5.6)	531 (5.9)	4 (0.3)	3 (1,1)
50 ms	526 (5.0)	527 (4.8)	545 (6.3)	18 (1.5)	1 (-0.2)
67 ms	530 (4.9)	530 (4.8)	553 (6.4)	23 (1.6)	-1 (-0.1)
83 ms	541 (4.9)	544 (5.6)	570 (5.3)	26 (-0.3)	3 (0.7)

Note. Orthographic priming is defined as the difference in target word recognition proficiency by orthographic primes relative to control primes. Phonological priming is the difference in target word recognition proficiency by phonological primes relative to orthographic primes.

Discussion

With respect to our question on the time course of orthographic and phonological code activation in the transparent Dutch orthography, the results of Study 1 show that although orthographic priming consistently affects word recognition latencies from 50 ms onwards, phonological primes provide no additional facilitation on top of this orthographic priming. The absence of phonological priming effects at short prime exposure durations is inconsistent with the Orthographic Depth hypothesis of early phonological influences in the transparent Dutch language. This finding thus suggests that phonological codes are not yet activated during the early lexical access stage in readers of a transparent orthography. However, an alternative explanation for the absence of phonological priming effects is also suggested by the Orthographic Depth hypothesis. It postulates that the phonological impoverishment of access representations renders these representations insensitive to small phonological differences. Therefore, strong phonological manipulations are required to identify phonological priming effects. Since phonological priming is defined as facilitation brought about by a phonological prime in comparison to an orthographic control prime that shares the same degree of orthographic overlap with the target, this implies that phonological and orthographic primes need to be phonologically sufficiently different to identify phonological priming effects. Thus, whereas a small phonological difference (e.g. *LONG* – *lont* – *lonc*) may be too subtle to be detected by the underspecified phonological codes in the access representations, a large phonological difference (e.g. *USE* – *yuice* – *douke*, example taken from Rastle & Brysbaert, 2006) could be detected. Studies that explicitly tested and supported the relation between the strength of the phonological manipulation and the presence of phonological priming effects have thus far only been conducted in the opaque Hebrew orthography (Frost, Ahissar, Gotesman & Tayeb, 2003; Gronau & Frost, 1997). The Orthographic Depth hypothesis assumes that the requirement for a strong phonological manipulation holds particularly in opaque orthographies, where access representations are least phonologically specified. However, it has been suggested that the absence of phonological priming effects in more transparent orthographies may also result from too subtle phonological manipulations (see Brysbaert, 2001). In fact, the straightforward connections between letters and speech sounds in the transparent Dutch orthography impede the construction of phonological and orthographic primes that are phonologically very different yet share the same degree of orthographic overlap with the target. Consequently, the phonological manipulations in the stimulus set of Study 1 were indeed generally subtle, mostly involving just one phoneme (e.g. the phonological prime '*vrient*' shares only one phoneme more with the target '*VRIEND*' than the orthographic prime '*vrienk*'). More specifically, orthographic primes did not only share orthographic, but also phonological overlap with the target (e.g. '*vrienk*' shares the first four phonemes with '*VRIEND*'). It is thus well possible that orthographic primes provided not only orthographic, but also phonological priming effects. Then the additional facilitation that could be provided by the phonological prime (*vrient*) would simply be too subtle to manifest in observable facilitation.

To tentatively test whether the presence of phonological priming effects depends on the strength of the phonological manipulations[2], we contrasted phonological priming effects for targets with a large and small difference in phonology between the phonological and orthographic primes. A difference in phonology was considered small when it affected only one phoneme (e.g. *VRIEND* – *vrient* – *vrienk*, where only the last phoneme /d/ is changed). A difference of two or three phonemes was referred to as large (e.g. *GOUD* (/gɔut/) – *gaut* (/gɔut/) – *geuf* (/gøf/), where both the second phoneme /ou/ and the last phoneme /d/ are changed). Since only ten of the ninety stimuli contained a large difference in phonology the analyses lacked power to establish statistically significant results. Nevertheless, as shown in Figure 1, phonological priming effects were now present, whereas orthographic priming was absent. This finding indeed suggests that the phonological differences in the general stimulus set were too subtle to be identifiable.

Therefore, we ran a second study to explicitly test whether phonological priming would become apparent if the phonological difference between phonological and orthographic primes were large enough. We replicated the time course analyses of Study 1 with two sets of stimuli: targets with small or large phonological differences between the phonological and orthographic prime. We aimed to answer two questions. First, is the presence of phonological priming effects dependent on the strength of the phonological manipulation in the transparent Dutch orthography, as in the opaque Hebrew orthography? And second, what is the time course of orthographic and phonological code activation in this transparent orthography?

[2] We refer to the phonological manipulation as contrasting targets with either a small or large phonological difference between the phonological and orthographic prime. However, this same phonological manipulation has also been described as contrasting phonological primes with either large or small orthographic overlap with the target.

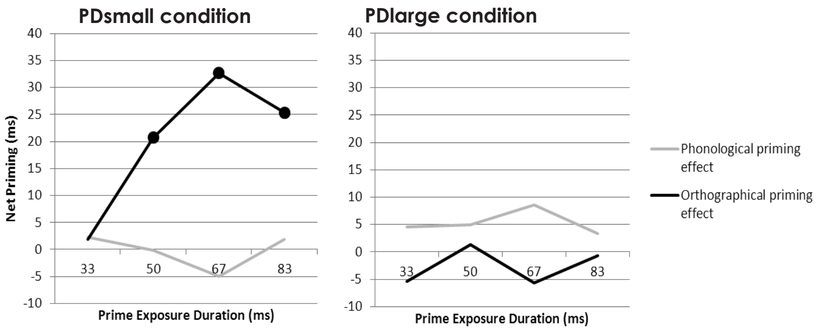

Figure 1. Net effects of phonological priming and net effects of orthographic priming as a function of prime exposure duration for targets with a small change in phonology between the phonological and orthographic prime (PDsmall condition, left panel) and for targets with a large change in phonology between the phonological and orthographic prime in Study 1 (PDlarge condition, right panel).
Note. Markers indicate a significant priming effect for p< .05.

Study 2

Method

Participants

96 Undergraduate and graduate students (77.1% female, mean age 21.02 years SD= 2.96) participated in Study 2. Inclusion criteria were similar to Study 1. Subjects participated either for course credit or a monetary reward. None of the participants had participated in Study 1.

Materials and Design

Target stimuli were 120 words with a length of 4 to 6 letters. The same procedure as in Study 1 was used to generate three nonword primes for each target word; a phonological prime, an orthographic prime, and a control prime. For 60 target words, the phonological difference between the phonological and orthographic prime was small (PDsmall), whereas for the other 60 target words this phonological difference was large (PDlarge). A small phonological difference was defined as a change of one phoneme between the phonological and orthographic prime (e.g. *vrient-vrienk*). A large phonological difference consisted of a change of two or more phonemes (e.g. *gaut* – *geuf*). As became clear from Study 1, targets that allow a large phonological difference between the phonological and orthographic prime are scarce in transparent orthographies. Therefore, loanwords that originate from (opaque) orthographies other than Dutch, yet are incorporated in the Dutch vocabulary, were included in the PDlarge condition. To ensure that these words would activate the typical word recognition processes of Dutch readers, a loan word was only included in the stimulus set if it was considered a true Dutch word according to the Dutch Language Association (Nederlandse Taalunie, 2005). In addition, great effort was taken to match the PDsmall and PDlarge targets as closely as possible on relevant lexical characteristics to assure that the two sets of targets would be similarly representative of the Dutch word recognition system. The

PDsmall targets were matched ($p<.05$) to the PDlarge targets on frequency per million, bigram frequency, number of neigbours (Nsize), mean frequency of neighbours and frequency of the highest frequent neighbour with the use of the Wordgen application (Duyck, Desmet, Verbeke & Brysbaert, 2004) for the Celex database (Baayen, Piepenbrock & van Rijn, 1993). The PDsmall targets and PDlarge targets were additionally matched on Subtlex-Nl frequency, which has been shown to be a more reliable frequency measure for Dutch words (Keuleers, Brysbaert & New, 2010). Furthermore, for each of the two target types all three prime types were matched on bigram frequency, mean frequency of neighbours and frequency of the highest frequent neighbour.

An additional 120 nonwords were generated to serve as foil targets in the lexical decision task, each accompanied by the same three types of nonword primes as the word targets; a phonological, orthographical and control prime. As in Study 1, foil targets were created by changing one or two letters of a word target. However, twelve PDlarge word targets required a change in three or four letters to create a pseudohomophone phonological prime. All foil targets were created such as to maintain the CVC-structure of their derivate target word. The foil targets did not differ significantly from the word targets in mean bigram frequency, number of neighbours, mean frequency of neighbours and frequency of the highest frequent neighbour. The manipulation on phonological difference that was applied to the word targets was maintained for the foil targets, resulting in 60 PDsmall foil targets, and 60 PDlarge foil targets. For both types of foil targets the three prime types were matched on bigram frequency, mean frequency of neighbours and frequency of the highest frequent neighbour. In the supplemental material, the stimulus sets are depicted in Table S3 and S4, and the lexical characteristics of the stimulus sets in Table S5.

Similar to Study 1, three different experimental lists were created, each including all 120 word targets and 120 foil targets divided in six blocks of 40 targets. PDlarge and PDsmall stimuli were intermixed in the experiment to reduce strategic effects. Each block contained 10 PDlarge targets, 10 PDsmall targets, 10 PDlarge foils and 10 PDsmall foils. The primes in the three lists did not differ with respect to mean bigram frequency, number of neighbours, mean frequency of neighbours and frequency of the highest frequent neighbor. The same four prime exposure durations as used in Study 1 were adopted: 33, 50, 67 and 83 ms. This resulted in a total number of 960 items for each participant.

Procedure

The procedure was identical to Study 1 yet Dell Optiplex 760 desktops, with ASUS VW222U lcd monitors were used, since these monitors allowed a more precise control of stimulus presentation durations.

Results

Data cleaning

Targets with a mean accuracy below 0.8 were excluded from further analyses. This led to the exclusion of sixteen targets[3]. Removal of these items maintained the match of word and nonword targets on number of letters, phonemes, syllables, mean bigram frequency, number of neighbours, mean frequency of neighbours and frequency of the highest frequent neighbor (for an overview of stimulus characteristics of the included items see Table S5 in the supplementary material). Only the reaction times of correct responses to word targets were analyzed (95.5% of the data for word targets). Premature responses were excluded by the removal of all responses below 250 ms (0.02% of the correct responses to word targets). For each participant and condition, responses exceeding two standard deviations above the mean reaction time were excluded (5.1% of the correct responses to word targets)[4].

To check whether the response latencies were influenced by speed/ accuracy trade-offs, we first calculated correlations between median RT of the correct responses and mean accuracy rates for each of the twelve prime type (phonological, orthographic and control prime) x prime exposure duration (33, 50, 67 and 83 ms) conditions. Correlations were all significantly negative (ranging between -.36 and -.68 in the PDsmall condition and between -.31 and -.59 in the PDlarge condition), which refutes the presence of speed-accuracy tradeoffs. Mean error percentages for each condition are depicted in Table 2. Further analyses are all based on response latencies, including correct responses only.

Table 2
Median target word recognition latencies in ms and error percentages (in parentheses) as a function of prime type and prime exposure duration in the PDsmall condition of Study 2

	Phonological prime vrient - VRIEND	Orthographic prime vrienk - VRIEND	Control prime claumf - VRIEND	Orthographic priming effect	Phonological priming effect
33 ms	588 (4.8)	584 (5.3)	600 (5.7)	16 (0.4)	-4 (0.6)
50 ms	567 (5.0)	571 (4.3)	593 (5.6)	22 (1.4)	4 (-0.7)
67 ms	568 (4.1)	569 (4.8)	604 (5.1)	35 (0.3)	1 (0.7)
83 ms	581 (5.0)	590 (4.3)	618 (5.7)	28 (1.4)	8 (-0.7)

Note. Orthographic priming is defined as the difference in target word recognition proficiency by orthographic primes relative to control primes. Phonological priming is the difference in target word recognition proficiency by phonological primes relative to orthographic primes.

[3] These included the PDsmall word targets 'klucht' meaning 'comedy', 'fjord' meaning 'fjord', 'smaad' meaning 'aspersion', 'locus' meaning 'locus', the PDlarge word targets 'foyer' meaning 'foyer', 'schub' meaning 'scale', 'bidon' meaning 'water bottle', 'pipet' meaning, 'pipette', 'geisha' meaning 'geisha', 'quote' meaning 'quote', 'twijg' meaning 'twig', and the nonword targets 'geleg', 'wraad', 'smicht' and 'schijl'.

[4] One participant had a normal RT pattern, but severely deviating RT's to control primed targets at 67 ms. Therefore, only these targets were removed from the analyses.

Data were analysed with a subject and item-level repeated measures ANOVA's on median response latencies in which contrast, prime type and prime exposure duration were the main within factors, and list (list 1, 2 and 3) was included as a dummy between-subject factor. Analyses showed a main effect of prime type ($F_1(2, 91) = 65.92$, $p < .001$; $F_2(2, 105) = 43.44$, $p < .001$), a main effect of exposure duration ($F_1(3, 90) = 6.96$, $p = .001$; $F_2(3, 104) = 28.15$, $p < .001$), an interaction effect between contrast and prime type ($F_1(2, 91) = 17.53$, $p < .001$; $F_2(2, 105) = 9.76$, $p < .001$), an interaction effect between contrast and exposure duration ($F_1(3, 90) = 8.91$, $p < .001$; $F_2(3, 104) = 4.36$, $p = .006$), an interaction effect between prime type and exposure duration ($F_1(6, 87) = 6.84$, $p < .001$; $F_2(6, 101) = 4.62$, $p < .001$), and a three-way interaction between contrast, prime type and exposure duration ($F_1(6, 87) = 2.87$, $p = .013$; $F_2(6, 101) = 3.55$, $p = .003$). Follow up analyses were conducted for the orthographic and phonological priming effect separately. In the analyses on the orthographic priming effect, the factor prime type encompassed the two levels 'orthographic prime' and 'control prime', and in the analyses on the phonological priming effect the factor prime encompassed the two levels 'phonological prime' and 'orthographic prime'. The analyses indicated that the three-way interaction between contrast, prime type and exposure duration was significant for the orthographic priming effect ($F_1(3, 90) = 4.48$, $p = .006$; $F_2(3, 94) = 5.37$, $p = .002$), but not for the phonological priming effect ($F_1(3, 91) = 1.31$, $p = .276$; $F_2(3, 94) = 2.07$, $p = .110$). The three-way interactions indicate differences between the time courses of priming effects in the PDsmall and PDlarge condition. Therefore, results were subsequently analyzed for PDsmall and PDlarge targets separately.

Orthographic and phonological priming effects in PDsmall targets

Data in the PDsmall condition were analysed with a subject and item-level repeated measures ANOVA on median response latencies in which prime type and prime exposure duration were the main within factors, and list (list 1, 2 and 3) was included as a dummy between-subject factor. Analyses showed a main effect of prime type ($F_1(2, 186) = 65.63$, $p < .001$; $F_2(2, 96) = 63.60$, $p < .001$), a main effect of exposure duration ($F_1(3, 279) = 5.70$, $p = .001$; $F_2(3, 144) = 10.06$, $p < .001$) and an interaction effect ($F_1(6, 558) = 4.34$, $p < .001$; $F_2(6, 288) = 6.91$, $p < .001$).

Repeated measures ANOVA's for the four prime exposure durations separately showed a significant main effect of prime type at all exposure durations (33 ms: $F_1(1.86, 173.33) = 6.56$, $p = .002$; $F_2(2, 96) = 9.29$, $p < .001$), 50 ms: $F_1(2, 186) = 24.49$, $p < .001$; $F_2(2,96) = 15.62$, $p < .001$, 67 ms: $F_1(2, 186) = 55.02$, $p < .001$; $F_2(2, 96) = 35.85$, $p< .001$, 67 ms: $F_1(2, 186) = 55.02$, $p < .001$; $F_2(2, 96) = 46.86$, $p < .001$, 83 ms: $F_1(2, 186) = 26.59$, $p < .001$; $F_2(2, 96) = 53.73$, $p < .001$).

As in Study 1, the orthographic priming effect was operationalized as the difference in median RT between the orthographic and control primed condition. Phonological priming was defined as the difference in median RT between the phonological and orthographic primed condition. These planned comparisons indicated that the orthographic priming effect was significant at each prime exposure duration (33 ms: $F_1(1, 93) = 10.68$, $p = .001$; $F_2(1, 48) = 11.93$, $p < .001$, 50 ms: $F_1(1, 93) = 32.04$, $p < .001$; $F_2(1, 48) = 21.03$, $p < .001$, 67 ms: $F_1(1, 93) = 82.95$, $p < .001$; $F_2(1, 48) = 68.42$, $p < .001$, 83 ms: $F_1(1, 93) = 26.82$, $p < .001$; $F_2(1, 48) = 50.44$, $p < .001$). The phonological priming effect was significant only at 83 ms (33 ms: $F_1(1, 93) = 0.73$, $p = .198$; $F_2(1, 48) = 0.02$, $p = .451$, 50 ms: $F_1(1, 93) = 1.09$, $p = .149$; $F_2(1, 48) = 0.22$, $p =.320$, 67 ms: $F_1(1, 93) = 0.05$, $p = .825$; $F_2(1, 48) = 0.09$, $p =.382$, 83 ms: $F_1(1, 93) = 3.26$, $p = .037$; $F_2(1, 48) = 11.07$, $p =.001$). Time courses are depicted in Figure 2.

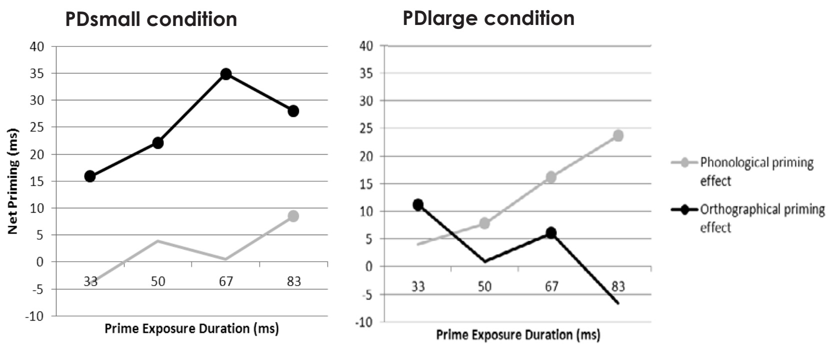

Figure 2. Net effects of phonological priming and net effects of orthographic priming as a function of prime exposure duration for for targets with a small change in phonology between the phonological and orthographic prime (PDsmall condition, left panel) and for targets with a large change in phonology between the phonological and orthographic prime in Study 1 (PDlarge condition, right panel) in Study 2.
Note. Markers indicate a significant priming effect for p< .05.

Orthographic and phonological priming effects in PDlarge targets

Median target word recognition latencies for the different prime type conditions and exposure durations are presented in Table 3. The data-analysis matched that of the PDsmall targets. Analyses showed a main effect of prime type ($F_1(2, 184) = 27.96$, $p < .001$; $F_2(2, 96) = 12.72$, $p < .001$), a main effect of exposure duration ($F_1(3, 276) = 6.71$, $p = .001$; $F_2(3, 144) = 21.92$, $p < .001$) and an interaction effect ($F_1(5.65, 519.34) = 3.74$, $p = .002$; $F_2(6, 288) = 2.23$, $p = .040$).

The repeated measures ANOVA's at each of the four prime exposure durations separately showed a main effect of prime type at every exposure duration (33 ms: $F_1(2, 186) = 6.57$, $p = .002$; $F_2(2, 96) = 4.83$, $p = .005$), 50 ms: $F_1(2, 186) = 3.27$, $p = .020$; $F_2(2,96) = 4.14$, $p = .010$, 67 ms: $F_1(1.90, 174.68) = 15.57$, $p < .001$; $F_2(2, 96) = 35.85$, $p < .001$, 67 ms: $F_1(2, 186) = 55.02$, $p < .001$; $F_2(2, 96) = 10.05$, $p < .001$, 83 ms: $F_1(2, 186) = 16.38$, $p < .001$; $F_2(2, 96) = 5.66$, $p = .005$).

Planned comparisons indicated that the orthographic priming effect was significant at the shortest prime exposure duration of 33 ms ($F_1(1, 93) = 6.55$, $p = .006$; $F_2(1, 48) = 8.26$, $p = .003$). At the longer priming durations, results were somewhat mixed. At 50 ms the orthographic priming effect was not significant, although there was a trend towards significance at the item level ($F_1(1, 93) = 0.11$, $p = .372$; $F_2(1, 48) = 2.30$, $p = .068$). At 67 ms there was a significant priming effect, which was not significant at the item level ($F_1(1, 92) = 3.20$, $p = .039$; $F_2(1, 48) = 0.52$, $p = .238$). At the longest prime exposure duration of 83 ms, there was a trend towards significant priming, but this was not significant at the item level ($F_1(1, 93) = 1.83$, $p = .090$; $F_2(1, 48) = 0.08$, $p = .390$). The phonological priming effect was not significant at 33 ms ($F_1(1, 93) = 0.86$, $p = .178$; $F_2(1, 48) = 0.11$, $p = .374$), yet became significant from 50 ms onwards (50 ms: $F_1(1, 93) = 4.92$, $p = .015$; $F_2(1, 48) = 2.20$, $p = .073$, 67 ms: $F_1(1, 92) = 16.84$, $p < .001$; $F_2(1, 48) = 13.28$, $p < .001$, 83 ms: $F_1(1, 93) = 28.70$, $p < .001$; $F_2(1, 48) = 8.65$, $p = .003$). Time courses are depicted in Figure 2.

Table 3
Median target word recognition latencies in ms and error percentages (in parentheses) as a function of prime type and prime exposure duration in the PDlarge condition of Study 2

	Phonological prime gaut - GOUD	Orthographic prime geuf - GOUD	Control prime peek - GOUD	Orthographic priming effect	Phonological priming effect
33 ms	575 (3.4)	579 (4.0)	590 (4.1)	11 (0.1)	4 (0.6)
50 ms	576 (3.2)	584 (3.6)	585 (4.1)	1 (0.5)	8 (0.4)
67 ms	571 (3.3)	587 (3.9)	593 (4.3)	6 (0.4)	16 (0.7)
83 ms	586 (2.9)	610 (4.6)	603 (4.0)	-7 (-0.6)	24 (1.7)

Note. Orthographic priming is defined as the difference in target word recognition proficiency by orthographic primes relative to control primes. Phonological priming is the difference in target word recognition proficiency by phonological primes relative to orthographic primes.

Discussion

The results of the PDsmall condition largely replicate the findings of Study 1: Orthographic primes facilitated visual word recognition from 33 ms onwards, whereas phonological primes did not provide additional facilitation during the earliest stages of visual word recognition. Phonological priming became apparent only at 83 ms. Together, these results indicate that phonological and orthographic priming effects do not show distinct time courses, but are intertwined, when stimuli contain the straightforward correspondences between orthography and phonology that are typical in a transparent orthography. In contrast, results from the PDlarge condition showed that when the correspondence between a word's spelling and pronunciation was not straightforward, orthographic and phonological primes did show distinct time courses. Orthographic primes facilitated visual word recognition only at the shortest prime exposure duration of 33 ms, and phonological priming effects became apparent from 50 ms onwards. The finding that phonological priming effects are consistently present from 50 ms onwards in words with a large phonological difference, yet appear only at 83 ms in words with a small phonological difference support the hypothesis that the presence of phonological priming effects depends on the strength of the phonological manipulation.

With respect to our key question concerning the time course of orthographic and phonological code activation in transparent orthographies, the PDlarge results indicate distinct time courses for orthographic and phonological priming effects, with phonological priming effects appearing shortly after orthographic priming effects. Interestingly, whereas orthographic priming effects were prominent at 33 ms they diminished shortly afterwards, and from 50 ms onwards, phonological priming effects were most dominant. This suggests that once orthographic codes are translated into phonological codes, phonological influences predominate the visual word recognition process in skilled readers of the transparent Dutch orthography.

What should be noted is that despite the similar findings in Study 1 and the PDsmall condition of Study 2, small differences exist. Most notably, orthographic priming effects became apparent from 50 ms onwards in Study 1, yet were already present at 33 ms in the PDsmall condition of Study 2. In addition, whereas phonological priming effects were completely absent in Study 1, they appeared at 83 ms in the PDsmall condition of Study 2. These differences suggest that the design of Study 2 was more sensitive, which may result from the enhanced matching of the lexical characteristics of stimuli in combination with a tighter control of stimulus presentation durations due to the use of desktops.

One finding requires further clarification. That is, both item and subject level analyses show clear orthographic priming at 33 ms which diminishes afterwards. However, at the subject level, orthographic priming becomes significant again at 67 ms (see Figure 1). One possible explanation for this peak is that around 67 ms an orthographical check on the assembled phonological code occurs, which is in line with Interactive Activation models that propose reciprocal interactions between sublexical orthographic and phonological processes (e.g. Grainger & Holcomb, 2009). However, this leaves unexplained why the orthographic priming effect at 67 ms appears solely at the subject level and not at the item level. Alternatively, it could be argued that the orthographic priming effect at 67 ms is an artifact. Future time course analyses in transparent orthographies are necessary to identify the nature of prelexical orthographic processes after phonological codes have been accessed.

General discussion

The primary aim of this study was to assess the time courses of orthographic and phonological code activation during visual word recognition in a transparent orthography. To this end, we investigated orthographic and phonological priming effects in skilled Dutch readers. The first study showed early and consistent orthographic priming effects, yet no additional phonological priming. Post hoc analyses suggested that the absence of phonological priming effects might have been due to the subtlety of the phonological manipulations, since phonological priming effects became more easily observable in the few stimuli that did allow a strong phonological manipulation. This seemed to indicate that in typical stimuli of a transparent orthography, the high interconnectivity of phonology and orthography results in intertwined orthographic and phonological priming effects, which, as a consequence prevents the investigation of individual time courses for orthographic and phonological code activation. Therefore, we decided to conduct a second study in which we explicitly contrasted stimuli with subtle and large phonological manipulations. The aim of this study was to establish whether the presence of phonological priming effects depends on the strength of the phonological manipulation. And if so, to investigate the time courses of orthographic and phonological priming. This second study confirmed that in the transparent Dutch orthography, similar to the opaque Hebrew orthography, strong phonological differences are a prerequisite to separate phonological from orthographic priming effects. When phonological differences are strong enough, it becomes clear that orthographic and phonological priming follow distinct time courses. Orthographic codes are activated initially, yet orthographic influences diminish quickly after this initial activation. Phonological codes are activated shortly after orthographic codes and remain influential throughout the lexical access process.

Although the relation between the presence of phonological priming effects and the strength of the phonological manipulation is often noted (e.g. Carreiras, Ferrand, Grainger & Perea, 2005; van Orden & Kloos, 2005), it had thus far only been established in Hebrew (Frost et al., 2003; Gronau & Frost, 1997). However, the Hebrew orthography allows inducing a large phonological difference between phonological and orthographic primes with only a small change in orthography, whereas in most orthographies, large phonological differences between the phonological and orthographic primes are accompanied by large orthographic differences (pointed out by Rastle and Brysbaert, 2006). The current study shows that the prerequisite of a strong phonological manipulation to identify phonological priming effects also holds in orthographies where phonology and orthography can be separated less easily. This finding corroborates near significant results from post hoc analyses in a masked priming perceptual identification task in Dutch (Brysbaert, 2001). The finding is also in line with bilingual studies showing that phonological priming can be identified only in situations with low orthographic overlap (Comesaña et al., 2012; Dimitropoulou, Duñabeitia & Carreiras, 2011b). Together, these findings suggest that the requirement for strong phonological manipulations to identify phonological priming effects is universal rather than characteristic of opaque orthographies. In terms of the Orthographic Depth hypothesis, this could be interpreted to indicate that the access representations of readers of transparent orthographies are as underspecified as those of readers of opaque orthographies, rendering them insensitive to small phonological differences. Alternatively, the requirement for a strong phonological manipulation may have other causes, and may not be indicative of the impoverishment of access representations. Future studies are clearly needed to specify the nature of access representations across orthographies. In any case, the finding that phonological priming effects are only observable with strong phonological differences is in line with a meta-analysis on phonological priming effects in English (Rastle & Brysbaert, 2006) that concluded that effect sizes of phonological priming are generally small. Although we do not aim to distinguish between models of visual word recognition, our findings are in line with strong phonological theories that consider phonology an essential part of the word recognition process, yet they are difficult to incorporate in weak phonological theories that consider phonological influences secondary (see Rastle & Brysbaert, 2006 page, 113-114).

The finding that orthographic and phonological code activation follow distinct time courses in a transparent orthography, with phonology being activated shortly after orthography, is in line with the results of Carreiras et al. (2009) in Spanish. However, Carreiras and his colleagues found orthographic and phonological priming effects on ERP waves but not on behavioural measures and attributed this to a lack of sensitivity of the behavioural measures. The current study shows that when the phonological manipulation is strong enough, distinct phonological and orthographic priming effects can be identified at the behavioural level as well in transparent orthographies. Our findings also extend the results of Brysbaert (2001), who, in a perceptual identification paradigm in Dutch, showed orthographic priming at both 29 and 43 ms, but phonological priming only at 43 ms. Despite the differences in experimental design, Brysbaerts results fit neatly in the time courses of phonological and orthographic code activation that are shown in the current study. Together, the findings suggest three stages during lexical access in the transparent Dutch orthography: During the first 30 ms, orthographic codes become activated. Between 30 and 50 ms these orthographic codes are translated into phonological codes, resulting in increasing phonological influences and diminishing influences of orthography. From around 50 ms onwards, phonology dominates the word recognition process. Interestingly, the time courses in the current study show remarkable similarities to the time courses in the opaque French orthography reported by Ferrand and Grainger (1993). The main difference resides in the timing of phonological codes becoming dominant. In French, phonological influences outperform orthographic influences from 67 ms onwards and thus slightly later than in Dutch readers. Although comparisons between results from different studies are always speculative due to differences in experimental design, the finding of earlier activation of phonological codes in readers of transparent as compared to opaque orthographies is in line with the Orthographic Depth hypothesis. This provides preliminary support for the hypothesis that the straightforward correspondences between orthographic and phonological codes in transparent orthographies allow for accelerated phonological code activation. However, the difference between the timing of phonological dominance in the two orthographies is rather small. It should be noted that the time courses in the current study are based on stimuli that were specifically selected to allow for the separation of orthography and phonology. As a consequence these stimuli contained less straightforward phoneme-grapheme correspondences than are typically present in the transparent Dutch orthography. Thus, although the stimulus material might have hampered the formation of orthography-phonology associations, Dutch readers seemed to be able to activate phonology more quickly than French readers. This raises the question how time courses of orthographic and phonological code activation manifest in stimuli with the straightforward grapheme-phoneme correspondences that are typical in transparent orthographies. However, the intertwined orthographic and phonological priming effects in these stimuli, as shown in Study 1 and the PDsmall condition of Study 2, suggest that the masked priming paradigm is not sufficiently sensitive to answer this question. Since the ERP technique allows identification of time course effects that remain hidden in behavioural measures, the addition of ERP measures to the current time course analyses of priming effects could provide useful additional information. ERP analyses might shed light on the time courses of orthographic and phonological code activation in targets with straightforward grapheme-phoneme correspondences that are typical of transparent orthographies. Moreover, the addition of ERP measures would allow more direct and more fine-grained analyses of time courses, since ERP's can be measured with high temporal resolution (Luck, 2005).

In conclusion, the current study contributes to our understanding of the activation and interrelation of orthographic and phonological codes during visual word recognition across orthographies. Time course analyses of priming effects in the transparent Dutch orthography provided two main conclusions. First, the straightforward grapheme-phoneme correspondences in typical words of transparent orthographies, result in intertwined orthographic and phonological priming effects. As a consequence, similar to opaque orthographies, strong phonological differences are a prerequisite to separate orthographic and phonological priming effects. Second, when phonological differences are strong enough, orthographic and phonological priming can be shown to follow distinct time courses in transparent orthographies. Orthography is accessed initially yet orthographic codes are quickly translated into phonological codes with phonological influences dominating the remainder of the lexical access stage. In line with the Orthographic Depth hypothesis, time courses seem to be indicative of earlier phonological code activation in transparent than opaque orthographies.

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Chapter 3

Time course analyses of orthographic and phonological priming effects in developing readers

Based on: Zeguers, M.H.T., Huizenga, H.M., Molen, M.W. van der & Snellings, P. (in revision). Time course analyses of orthographic and phonological priming effects in developing readers.

Abstract

It has been assumed that fluent reading requires efficient integration of orthographic and phonological codes. However, it is thus far unclear how this integration process develops when children learn to become fluent readers. Therefore, we used masked priming to investigate time courses of orthographic and phonological code activation in children at incremental levels of reading development (2nd, 4th and 6th grade). The first study used targets with small phonological differences between phonological and orthographic primes, which are typical in transparent orthographies. The second study manipulated the strength of the phonological difference between prime and target to clarify whether phonological difference influences phonological priming effects. Results in both studies showed that orthographic priming effects became facilitative at increasingly short durations during reading development, but phonological priming was absent. These results are taken to suggest that development of reading fluency is accompanied by increased automatization of orthographic representations. The absence of phonological priming suggests that developing readers cannot yet activate phonological codes automatically.

Introduction

In transparent orthographies, children acquire grapheme-phoneme correspondences rapidly, which allows them to read highly accurate within the first year of reading instruction (Seymour, 2003; de Jong & van der Leij, 1999). Reading fluency, on the other hand, develops more gradually (Landerl & Wimmer, 2008; Vaessen & Blomert, 2010) and distinguishes between good and poor readers (de Jong & van der Leij, 2003). It has been assumed that fluency results from the efficiency with which a reader can integrate orthography and phonology (Breznitz, 2002; Ehri, 2005; Fraga González et al., 2015; Hahn, Foxe & Molholm, 2014; Perfetti & Hart, 2001). In line with this assumption, brain imaging studies show that orthography-phonology integration at the level of individual letters is related to reading fluency (Blau, van Atteveldt, Ekkebus, Goebel & Blomert, 2009; Blau et al., 2010) and that cortical area's associated with orthography-phonology integration show deviant activation in persons with dyslexia, who are known to be characterized by reading fluency deficits (Cao, Bitan & Booth, 2008; Horwitz, Rumsey & Donohue, 1998; Shaywitz et al., 2002; Žarić et al., 2014).

Important insights into the process of orthography-phonology integration in skilled readers has come from studies employing masked priming. This technique involves the presentation of a target word, which is preceded by a briefly presented and masked prime word. It is generally assumed that the overlapping features between prime and target allow for the word recognition process to start at perception of the prime, thus resulting in a time advantage at the moment the target is perceived (Forster, Mohan & Hector, 2003). Since primes can be presented very briefly, their influence must affect the earliest phases of the word recognition process. Therefore, the masked priming paradigm allows investigating the early lexical access stage when orthography-phonology connections are activated. In time course analyses of masked priming effects, the exposure duration of orthographic and phonological primes is manipulated in order to examine when orthographic and phonological information become available during visual word recognition (Ferrand & Grainger, 1992; 1993; 1994). The paradigm encompasses a lexical decision task in which target words are preceded by three nonword primes: 1) a phonological prime, which is pronounced identical, yet spelled slightly different than the target (a so called pseudohomophone, e.g. *bote* – *BOAT*), 2) an orthographic prime, which shares the same degree of orthographic overlap with the target as the phonological prime, but is not a pseudohomophone (e.g. *boti* – *BOAT*), and 3) a control prime, which shares neither orthography nor phonology with the target (e.g. *rune* – *BOAT*). Faster recognition of a target that is preceded by an orthographic prime in comparison to a control prime is referred to as orthographic priming, and indicates that the orthographic overlap between prime and target facilitates target recognition. Phonological priming is defined as the difference in recognition rate in the phonological as compared to the orthographic prime condition. Since both orthographic and phonological primes share the same degree of orthographic overlap with the target, any additional facilitation by the phonological prime is assumed to result from shared phonology.

Time course analyses in skilled Dutch readers indicated that orthographic and phonological processes follow distinct time courses (Zeguers, Snellings, Huizenga & van der Molen, 2014). Orthography is accessed initially, yet within 50 milliseconds orthographic codes are translated into phonological codes, with phonological influences dominating the remainder of the lexical access stage. This shows that skilled readers integrate orthography and phonology very quickly during word recognition, indicating that phoneme-grapheme correspondences are highly automatized. Similar findings were found in skilled readers of French (Ferrand & Grainger, 1993), Chinese (Perfetti & Tan, 1998) and English (Grainger, Kiyonaga & Holcomb, 2006).

This insight into the time course of orthographic and phonological code activation in skilled readers raises the question how these processes evolve during reading development. However, time course analyses of orthographic and phonological priming have not been conducted with developing readers in visual word recognition tasks. In a naming task, Booth, Perfetti and MacWhinney (1999) did investigate developmental effects of orthographic and phonological priming at two prime exposure durations. Results showed that younger readers exhibited smaller phonological priming effects at 30 ms than at 60 ms, whereas for older readers priming effects were similar at both durations. This indicates that with increasing reading skill, phonological information becomes effective at shorter durations, suggesting more rapid convergence between orthographic and phonological information. However, this study did not use lexical decision, but adopted a naming task instead. Consequently, these results apply to reading aloud, where the computation of a phonological code is clearly more essential than in visual word recognition. In addition, since orthographic and phonological priming effects were present at both durations, this leaves unanswered the question when orthographic and phonological information become available.

Theoretical accounts of reading development make contradictory predictions with respect to developmental changes in priming effects. These predictions have been supported with studies on the magnitude, but not yet on the timing of priming effects. First, the lexical-quality hypothesis (Perfetti, 2007; Perfetti & Hart, 2002) argues that when reading skill improves, grapheme-phoneme connections of word representations become more precise, thereby allowing more efficient activation of orthographic and phonological information. With respect to priming, the lexical-quality hypothesis predicts that both orthographic and phonological primes become increasingly beneficial during reading development. Accordingly, Booth et al. (1999) reported increases in orthographic and phonological priming effects with increasing reading skill. In addition, Comesaňa, Soares, Marcet and Perea (2016) used consonant/vowel asymmetries in letter position priming as an indicator of phonological priming, and found this asymmetry to be present in adults but not yet in children. Second, dual-route models (Coltheart et al., 1993; 2001) propose a developmental shift in word recognition strategy, from slow, serial phonological decoding to predominantly quick, parallel letter activation, which directly accesses orthographic representations. Consequently, the dual-route model predicts increases in orthographic influences during reading development (similar to the lexical-quality hypothesis; e.g., Lété and Fayol, 2013; Ziegler, Bertrand, Lété and Grainger, 2014), whereas phonological priming effects have been assumed to either remain stable (Ziegler et al., 2014) or decrease with reading skill (see post-hoc analyses of Davis, Castles and Iakovidis, 1998). Third, according to the lexical tuning theory (Castles, Davis, Cavalot & Forster, 2007; Castles, Davis & Letcher, 1999), reading development is accompanied by expansion of the orthographic lexicon. Consequently, the word recognition system needs to employ increasingly strict criteria to distinguish a target word from similar-looking other words in the lexicon. The lexical tuning theory therefore predicts reduced sensitivity to the similar-looking orthographic primes during development, which is supported by findings of decreases in orthographic priming effects in children with incremental reading skills (Acha & Perea, 2008; Castles et al., 1999, 2007).

In sum, masked priming results are inconsistent as to whether priming effects decrease or increase during the development of visual word recognition. Moreover, since time course analyses have not been conducted, it is unknown to what extent developmental changes in orthographic and phonological processes influence the timing of priming effects. The lexical-quality hypothesis assumes increasingly efficient activation of orthographic and phonological information. This hypothesis thus predicts that both orthographic and phonological priming effects commence increasingly early when reading skill improves. Dual-route theories also predict increasingly early appearance of orthographic priming effects, due to increased use of quick, direct access to orthographic representations. However, phonological recoding is assumed to become less dominant during reading development, and to become involved only after direct orthographic access failed to find a solution in skilled readers. Therefore, it could be argued that dual-route models predict phonological priming effects to occur increasingly late during development. Alternatively, since phonological recoding is assumed to be a slow process, it may commence too late to exist in the initial phases of word recognition when priming occurs. Accordingly, phonological priming effects could be absent in all age groups. Finally, since the lexical tuning theory assumes diminishing sensitivity to orthographic primes with increasing reading skill, this could result in increasingly delayed activation of orthography, and thus a developmental increase in latencies of orthographic priming effects.

Therefore, in the current study, we will conduct time course analyses of orthographic and phonological priming effects during silent word recognition in children at incremental levels of reading proficiency. We focus on reading development in the transparent Dutch orthography. We study children in grades 2, 4 and 6 since at these ages children have generally passed the initial reading stage of acquiring grapheme-phoneme correspondences. They can read familiar words accurately without the need to decode out loud, yet still progress in their fluency of word recognition. Previous studies have shown that phonological priming effects are generally small (Rastle & Brysbaert, 2006). Therefore, we investigate a relatively broad time period, with priming durations between 33 and 83 ms and include large samples of each age group to enhance the sensitivity for the detection of priming effects. By outlining the time courses of orthographic and phonological priming effects, we will determine how early orthographic codes can be activated and coupled to phonological codes during reading development.

Study 1

Method

Participants

One hundred and four grade 2 students (46% female, mean age 7,7 years), 102 grade 4 students (57% female, mean age 9.7 years) and 123 grade 6 students (54% female, mean age 11.8 years) participated in Study 1. The number of participants was based on a-priori power analyses. The children were recruited from two small city elementary schools. Parents received informed consent forms. All participating children were native speakers of Dutch and none suffered from vision, hearing or language problems. Participants received a small present for participation. The study was approved by the ethical review board.

Materials and Design

The stimulus set consisted of 90 words and 90 pseudowords with lengths of 4, 5 or 6 letters. The targets were selected as to allow the generation of three pronounceable and syntactically correct nonword primes: 1) a phonological prime, which was a pseudohomophone of the target (e.g. vrient – VRIEND [FRIEND]), 2) an orthographic prime with the same number of shared letters with the target as the phonological prime, but not homophonic (e.g. vrienk – VRIEND) and 3) a control prime that had no letters in common with the target (e.g. claumf – VRIEND). The stimulus set was identical to the stimulus set used in a previous experiment with skilled adult readers (for characteristics of stimuli and stimuli selection see Zeguers et al, 2014 or chapter two of the current thesis).

Tasks

Primed lexical decision task

The primed lexical decision task was the same as used previously with skilled adult readers (Zeguers et al., 2014 or chapter two of the current thesis). In the current study, the task was presented on nine identical 15- inch Acer Travelmate 4150 laptops, running Presentation (www.neurobs.com). Following Ferrand & Grainger (1992; 1993; 1994), prime exposure durations were 33, 50, 67 and 83 ms.

Categorization task

With a short categorization task, the children were introduced to the stimulus material of the lexical decision task in order to reduce learning effects. In addition, the task familiarized the children with the concept of nonwords. In the paper-and-pencil categorization task, all 180 word and nonword targets were printed in sets of four in quasi-random order. Children were instructed to indicate whether the four items within a set were a) all words, b) all nonwords or c) a combination of words and nonwords. Children responded by selecting one of three pictures related to the three response options.

Procedure

Children participated in the experiment during school hours in a silent room in their school. The experimental tasks were presented in five testing sessions: the categorization task and four exposure duration conditions of the lexical decision task (in randomised order). All testing sessions were one week apart.

Results

Preprocessing

Data cleaning was conducted in a seven-step procedure. First, trials in which prime duration deviated more than 7 ms from the intended prime duration were removed (0.04% of the data). Second, premature responses were excluded by the removal of all responses below 250 ms (0.6% of the data). Third, targets to which grade 2 participants performed at chance level (<.57) were considered unfamiliar. This led to the removal of ten targets (the words "chaos", "cirkel", "radijs", "succes", "file", "actie", "vonk" and "recept", and the pseudowords "fink" and "sekker", 5.5% of the data). Fourth, conditions were removed in which children performed at chance level (<.57, 0.54% of the data). Fifth, the correct word reaction times (RTs) were transformed to their natural logarithmic (log RT) in order to normalize the RT distributions. Sixth, outlier trials were removed by excluding trials with log RTs >2.5 standard deviations above the mean log RT in a particular (prime type x prime duration) condition (1.63% of the correct word trials). Seventh, outlier participants were excluded, by removing participants with mean log RT > 2.5 standard deviations above the mean log RT in a particular (grade) group. This led to removal of one grade 8 participant. Non-transformed mean RTs for all twelve prime type x prime exposure duration conditions for all three grade groups are depicted in Table 1.

Table 1
Mean target word recognition rate in ms (and accuracy between brackets) as a function of prime type and prime exposure duration in Study 1

	Phonological prime vrient - VRIEND	Orthographic prime vrienk - VRIEND	Control prime claumf - VRIEND	Orthographic priming effect	Phonological priming effect
Grade 2					
33 ms	1763,70 (.78)	1796,76 (.78)	1802,69 (.78)	5,92	33,06
50 ms	1771,25 (.78)	1788,93 (.78)	1799,97 (.78)	11,04	17,68
67 ms	1760,28 (.76)	1793,93 (.77)	1817,14 (.76)	23,21*	33,64
83 ms	1750,76 (.78)	1742,64 (.78)	1838,30 (.77)	95,66***	-8,12
Grade 4					
33 ms	1097,60 (.91)	1112,73 (.92)	1102,10 (.91)	-10,63	15,13
50 ms	1066,88 (.91)	1093,33 (.91)	1091,60 (.91)	-1,73	26,45*
67 ms	1121,97 (.91)	1137,83 (.91)	1139,36 (.91)	1,53	15,86
83 ms	1061,19 (.90)	1083,85 (.91)	1114,30 (.91)	30,45***	22,66
Grade 6					
33 ms	875,97 (.92)	873,48 (.93)	877,65 (.94)	4,17	-2,48
50 ms	882,91 (.94)	893,48 (.94)	914,08 (.93)	20,60***	10,57
67 ms	878,42 (.93)	885,27 (.93)	897,73 (.92)	12,47***	6,85
83 ms	853,48 (.93)	868,99 (.93)	907,63 (.93)	38,64***	15,51

Note. Orthographic priming is defined as the difference in speed of target word recognition between orthographic primes and control primes. Phonological priming is the difference in speed of target word recognition between phonological primes and orthographic primes
* $p < .10$, ** $p < .05$, *** $p < .01$.

Time course analyses of priming effects

The data were analysed with a mixed-effects model on the log transformed RT's of the correct responses. The main advantage of a mixed-effects analysis is that both items and subjects can be incorporated as random effects in one analysis, which dissolves the need for separate item- and subject-level analyses (Baayen, Davidson & Bates, 2008). Analyses were performed with the lme4 (Bates, Maechler, Bolker & Walker, 2015) and lmerTest (Kuznetsova, Brockhoff & Chris-Tensen, 2013) R packages.

To identify the time courses of orthographic and phonological priming effects, analyses were performed for each of the three age groups and each of the four prime exposure durations separately. In the analyses, the orthographic priming effect was operationalized as the mean log RT difference between the orthographic and control prime conditions. Phonological priming was defined as the mean log RT difference between the phonological and orthographic prime conditions. In the mixed–effects analysis, target and subject were included as random effects (i.e. as random intercepts). Prime type (orthographic or control prime in the analyses on orthographic priming, phonological and orthographic prime in the analyses on phonological priming) was included as fixed effect.

Grade 2. Orthographic priming was not significant at 33 ms ($t(2040.64) = -0.47$, $p = .640$) and 50 ms ($t(89.64) = -1.05$, $p = .296$). There was a trend towards significant orthographic priming at 67 ms ($t(3142.91) = -1.81$, $p = .071$), but only at 83 ms did the effect become truly significant ($t(84.30) = -3.74$, $p < .001$). The phonological priming effect was not significant at any of the four prime exposure durations (33 ms: $t(86.68) = -0.29$, $p = .775$; 50 ms: $t(1150.04) = 0.29$, $p = .775$; 67 ms: $t(2186.83) = -0.51$, $p = .609$; 83 ms: $t(56.89) = -0.16$, $p = .876$).
Grade 4. There were no orthographic priming effects at 33 ms ($t(92.44) = 0.30$, $p = .763$), 50 ms ($t(100.13) = -1.17$, $p = .243$), and 67 ms ($t(61.92) = -1.50$, $p = .139$). Orthographic priming was present at 83 ms ($t(84.30) = -3.74$, $p <.001$). Phonological priming was not significant at any of the four prime exposure durations, although there was a trend toward significance at 50 ms (33 ms: ($t(97.20) = -0.81$, $p = .420$; 50 ms: $t(94.00) = -1.76$, $p = .082$; 67 ms: $t(71.18) = -1.02$, $p = .312$; 83 ms: $t(52.84) = -1.11$, $p = .271$).
Grade 6. Orthographic priming was absent at 33 ms ($t(78.51) = -1.30$, $p = .199$), but clear orthographic priming emerged from 50 ms onward (50 ms: $t(70.58) = -3.30$, $p = .002$; 67 ms: $t(70.56) = -2.77$, $p = .007$; 83 ms: $t(81.36) = -5.50$, $p <.001$). Phonological priming was not present at any of the prime exposure durations (33 ms: $t(112.78) = 0.47$, $p = .642$; 50 ms: $t(121.02) = -0.95$, $p = .346$; 67 ms: $t(64.10) = -0.95$, $p = .347$; 83 ms: $t(69.65) = -1.26$, $p = .211$).

Discussion

The results of Study 1 show clear orthographic priming effects in all three age groups. Amongst 2nd and 4th grade students, this orthographic facilitation occurs only at 83 ms, whereas 6th grade students can already benefit from orthographic priming at 50 ms. This indicates that children from 7 years onwards can use prelexical orthographic information to facilitate word recognition fluency, and that this orthographic information can be accessed at increasingly short durations during reading development. However, the results of Study 1 do not show phonological priming effects in any of the age groups. The absence of phonological priming effects could be interpreted to suggest that phonological codes are not yet activated during the early lexical access stage in beginning readers. However, an alternative explanation is provided by a previous study on the time course of phonological and orthographic priming in adults (Zeguers, et al., 2014). This study showed that strong phonological differences between orthographic and phonological primes are required to identify phonological priming effects. That is, in the transparent Dutch orthography, a letter is generally pronounced identically across words. This impedes the construction of phonological and orthographic primes that are phonologically very different yet share the same degree of orthographic overlap with the target. Consequently, phonological manipulations in typical Dutch words are generally subtle. This was also the case in Study 1. The difference mostly involved only one phoneme (e.g. the phonological prime '*vrient*' shares only one phoneme more with the target '*VRIEND*' than the orthographic prime '*vrienk*'). As a consequence, orthographic primes did not only have orthographic, but also considerable phonological overlap with the target (e.g. '*vrienk*' shares the first four phonemes with '*VRIEND*'). The Zeguers et al. (2014) study showed that in adults, these typical orthographic primes provided not only orthographic, but also phonological priming effects. Therefore, the additional facilitation that could be provided by the phonological prime was too subtle to manifest in observable phonological priming. However, when primes were selected such as to allow a large phonological difference (involving at least two phonemes) between the orthographic and phonological prime, phonological priming effects did become observable.

In order to test whether strong phonological manipulations are required to separate orthographic and phonological priming effects in children as well, we conducted a second study in which we performed the time course analyses of Study 1 using two sets of stimuli: Targets with small and large phonological differences between the phonological and orthographic primes. We aimed to answer two questions: (1) Do phonological priming effects in children depend on phonological differences, as they do in adults? (2) What is the time course of orthographic and phonological code activation in children?

Study 2

Method

Participants

In Study 2, 99 grade 2 students (53% female, mean age 8,1 years), 92 grade 4 students (57% female, mean age 10,2 years) and 120 grade 6 students (52% female, mean age 12,2 years) participated. The number of participants was based on a priori power analyses. The children were recruited from four elementary schools in urban and suburban areas. Parents received informed consent forms. All participating children were native speakers of Dutch and none suffered from vision, hearing or language problems. None of the children participated in Study 1. The study was approved by the ethical review board.

Materials and Design

The stimulus set was used previously in a masked priming experiment with advanced, adult readers (for characteristics of stimuli and stimuli selection see Zeguers et al., 2014 or chapter two in the current thesis). Target stimuli were 120 words with a length of 4 to 6 letters. For 60 target words, the phonological difference between the phonological and orthographic prime was small (PDsmall), whereas for the other 60 target words this phonological difference was large (PDlarge). A small phonological difference was defined as a change of one phoneme between the phonological and orthographic prime (e.g. *vrient-vrienk* for the target *VRIEND*). A large phonological difference consisted of a change of two or more phonemes (e.g. *gaut* – *geuf* for the target *GOUD [GOLD]*). It should be noted that the phonological manipulation concerns the phonological difference between the phonological and orthographic prime, but not between the phonological prime and the target. Both in the PDsmall and PDlarge condition, the phonological primes were pseudohomophones of the target and thus phonologically identical to the target. The stimulus set was initially selected for use with adult readers. Hence targets in the PDsmall and PDlarge conditions were matched on frequency estimates from a corpus based on adult literature (Celex, Baayen, Piepenbrock & van Rijn, 1993). To rule out the possibility that differences between the PDsmall and PDlarge conditions would result from differences in target familiarity to the participating children, we examined whether targets in the two conditions were also matched on frequency estimates from a corpus based on child literature (Basilex, Tellings, Hulsbosch, Vermeer & van den Bosch, 2014). A t-test indicated that the frequency of appearance in children's literature was similar for the PDsmall and PDlarge targets ($t(118)=0.56$, $p=0.574$). Although frequency and familiarity are not equivalent, this suggests that the targets in the two conditions were equally familiar to the children.

Tasks

Primed lexical decision task

The primed lexical decision task was designed and administered in an identical manner as in Study 1.

Word training

The stimuli of the lexical decision task were selected as to allow a large phonological difference between the phonological and orthographic prime in the PDlarge condition. Since such words are uncommon in the transparent Dutch orthography, the stimulus set contained many words that were either of low frequency or comprised an irregular spelling pattern. A four-day word training was implemented prior to the lexical decision experiment to assure that all participants were familiar with both the pronunciation and spelling of all stimuli.

To assess whether children had indeed learned the target stimuli during the training, a word-reading test was presented prior to the first lexical decision task. Children were provided with a wordlist containing all 120 target stimuli, and asked to read these words aloud. All participating children could correctly pronounce at least 65 of the 120 targets (63%), and 95% of the children pronounced more than 96 targets (80% of the total number of targets) correctly. This indicates that most target items were well learned by the vast majority of the participants.

Procedure

Children first followed the word training during four days within one week. Training was provided in their classroom. During the next week, children completed the four exposure duration conditions of the lexical decision task, on four consecutive days. The lexical decision task was conducted in a silent room in the children's school. The training and experimental sessions took part during school hours.

Results

Preprocessing

Data cleaning was similar to Study 1. This led to the following removal percentages: Step 1: 1.54%, step 2: 1.,54%, step 3: 0.83% (the targets "quote" and "coach"), step 4: 2.35%, step 6: 1.39% of correct word trials, and step 7: 0% (no outlier participants). Non-transformed mean RTs for all twelve prime type x prime exposure duration conditions for all three grade groups are depicted in Tables 2 (PDsmall condition) and 3 (PDlarge condition).

Table 2
Mean target word recognition rate in ms (and accuracy between brackets) as a function of prime type and prime exposure duration in the PDsmall condition of Study 2

	Phonological prime vrient - VRIEND	Orthographic prime vrienk - VRIEND	Control prime claumf - VRIEND	Orthographic priming effect	Phonological priming effect
Grade 2					
33 ms	1427,10 (.87)	1372,98 (.86)	1404,56 (.87)	31,58	-54,12
50 ms	1348,39 (.88)	1308,16 (.87)	1375,30 (.88)	67,14***	-40,23
67 ms	1371,10 (.87)	1374,23 (.88)	1440,28 (.86)	66,05***	3,13
83 ms	1368,09 (.87)	1358,74 (.87)	1442,00 (.87)	83,26***	-9,35
Grade 4					
33 ms	1020,53 (.93)	1041,22 (.91)	1048,13 (.91)	6,91	20,69*
50 ms	1015,79 (.93)	1017,66 (.92)	1036,43 (.92)	18,77**	1,87
67 ms	1008,45 (.92)	1029,46 (.93)	1071,23 (.93)	41,77***	21,01
83 ms	1001,38 (.93)	1039,48 (.92)	1057,55 (.92)	18,07*	38,1***
Grade 6					
33 ms	828,09 (.94)	832,48 (.95)	862,34 (.93)	29,86***	4,39
50 ms	854,71 (.93)	840,82 (.93)	859,31 (.93)	18,49***	-13,89
67 ms	830,41 (.93)	822,42 (.95)	863,66 (.93)	41,24***	-7,99
83 ms	812,59 (.93)	820,78 (.94)	866,18 (.92)	45,4***	8,19

Note. Orthographic priming is defined as the difference in speed of target word recognition between orthographic primes and control primes. Phonological priming is the difference in speed of target word recognition between phonological primes and orthographic primes
* p < .10, ** p < .05, *** p < .01.

Table 3
Mean target word recognition rate in ms (and accuracy between brackets) as a function of prime type and prime exposure duration in the PDlarge condition of Study 2

	Phonological prime vrient - VRIEND	Orthographic prime vrienk - VRIEND	Control prime claumf - VRIEND	Orthographic priming effect	Phonological priming effect
Grade 2					
33 ms	1386,86 (.84)	1362,90 (.83)	1379,20 (.84)	16,3	-23,96
50 ms	1361,57 (.86)	1350,24 (.85)	1351,63 (.85)	1,39	-11,33
67 ms	1371,76 (.84)	1398,07 (.86)	1405,81 (.84)	7,74	26,31*
83 ms	1370,20 (.85)	1377,89 (.85)	1389,39 (.83)	11,5	7,69
Grade 4					
33 ms	1028,31 (.93)	1023,76 (.92)	1029,15 (.92)	5,39	-4,55
50 ms	1022,62 (.93)	1011,29 (.92)	1013,03 (.91)	1,74	-11,33
67 ms	1013,21 (.92)	1039,60 (.93)	1073,96 (.91)	34,36**	26,39**
83 ms	1014,48 (.92)	1039,30 (.92)	1038,33 (.91)	-0,97	24,82
Grade 6					
33 ms	832,47 (.94)	834,25 (.94)	824,96 (.95)	-9,29	1,78
50 ms	840,17 (.94)	840,88 (.94)	844,58 (.93)	3,7	0,71
67 ms	827,29 (.95)	820,92 (.94)	855,67 (.94)	34,75***	-6,37
83 ms	817,34 (.95)	828,87 (.94)	845,21 (.94)	16,34*	11,53**

Note. Orthographic priming is defined as the difference in speed of target word recognition between orthographic primes and control primes. Phonological priming is the difference in speed of target word recognition between phonological primes and orthographic primes
* $p < .10$, ** $p < .05$, *** $p < .01$.

Time course analyses of priming effects

The method of data analysis was similar to Study 1, with Phonological difference (PDlarge, PDsmall) included as additional fixed effect.

Small phonological difference

Grade 2. Orthographic priming was not present at 33 ms ($t(58.44) = -0.60$, $p = .553$), yet became signigicant from 50 ms onwards (50 ms: $t(89.00) = -3.93$, $p < .001$; 67 ms: $t(58.33) = -2.82$, $p = .006$; 83 ms: $t(57.88) = -3.43$, $p = .001$). The phonological priming effect was never significant (33 ms: $t(57.52) = 0.47$, $p = .639$; 50 ms: $t(86.13) = 1.09$, $p = .278$; 67 ms: $t(44.17) = -0.01$, $p = .988$; 83 ms: $t(58.90) = 0.09$, $p = .928$).
Grade 4. There were no orthographic priming effects at 33 ms ($t(1936.90) = -0.68$, $p = .496$). However, orthographic priming was significant at 50 ms ($t(742.98) = -2.38$, $p = .018$) and 67 ms ($t(38.01) = -3.95$, $p < .001$) and showed a trend toward significance at 83 ms ($t(80.63) = -1.79$, $p = .078$). Phonological priming was absent at the first three prime exposure durations, although there was a trend toward significant priming at 33 ms (33 ms: $t(40.86) = -1.75$, $p = .088$; 50 ms: $t(79.63) = -0.16$, $p = .874$; 67 ms: $t(53.39) = -1.57$, $p = .123$. However, phonological priming became significant at 83 ms ($t(57.20) = -3.50$, $p < .001$)
Grade 6. Orthographic priming was significant at all durations (33 ms: $t(88.04) = -3.58$, $p < .001$; 50 ms: $t(99.73) = -3.14$, $p = .002$; 67 ms: $t(97.65) = -6.04$, $p < .001$; 83 ms: $t(40.58) = -$

7.00, p <.001). Phonological priming, on the other hand, was never significant (33 ms: t(93.26) = -0.58, p = .565; 50 ms: t(106.12) = 1.27, p = .207; 67 ms: t(58.00) = 0.77, p = .446; 83 ms: t(44.42) = -1.47, p = .148).

Large phonological difference

Grade 2. There were no orthographic priming effects at any of the exposure durations (33 ms: t(78.70) = -0.14, p = .890; 50 ms: t(2570.50) = -0.40, p =.691; 67 ms: t(84.33) = -0.03, p = 975; 83 ms: t(46.22) = -1.45, p =.153). Phonological priming was also never significant, although there was a trend toward significant priming at 67 ms (33 ms: t(78.97) = 0.26, p = .799; 50 ms: t(2064.85) = 0.37, p = .710; 67 ms: t(89.89) = -1.90, p = .06; 83 ms; t(73.40) = 0.02, p = .988).

Grade 4. Orthographic priming effects were not significant at 33 ms (t(86.61) = -0.06, p = .951), 50 ms (t(42.49) = -0.61, p = .542) and 83 ms (t(80.19) = -0.68, p = .501), yet were present at 67 ms (t(47.26) = -2.50, p = .016). Similarly, phonological priming was absent at 33 ms (t(51.90) = -0.08, p = .935), 50 ms (t(79.03) = 0.09, p = .928) and 83 ms (t(44.66) = -1.28, p = .205), but was significant at 67 ms (t(80.15) = -2.00, p = .049).

Grade 6. Orthographic priming was absent at 33 ms (t(48.04) = 0.43, p =.668) and 50 ms (t(111.56) = -0.73, p =.469), but became facilitative at 67 ms (t(65.08) = -3.12, p <.001) and showed a trend toward significance at 83 ms (t(107.69) = -1.67, p =.098). Phonological priming was not significant at the shortest three exposure durations (33 ms: t(51.15) = -0.35, p = .730; 50 ms: t(1506.35) = -0.58, p = .565; 67 ms: t(58.97) = 0.64, p = .524), but became significant at 83 ms: t(54.79) = -2.69, p = .010.

Discussion

In Study 2, the results in the PDsmall condition were largely similar to the findings from Study 1. As in Study 1, children from all three grade levels experienced facilitation from orthographic primes during visual word recognition and this orthographic facilitation affected the word recognition process at increasingly early stages when children became more proficient readers. These results support the suggestion that orthographic information becomes increasingly early accessible during reading development. As in Study 1, facilitation from phonological primes did not consistently exert influence on the visual word recognition process in any of the three grade levels. The finding of orthographic priming effects in the absence of phonological priming effects is in line with the hypothesis derived from Study 1, that the small phonological differences in the PDsmall targets result in intertwined orthographic and phonological priming effects, thereby preventing the finding of distinct phonological priming effects. According to this hypothesis, orthographic and phonological effects should be distinguishable in targets with large phonological differences. However, results from the PDlarge condition showed neither consistent orthographic nor phonological priming in any of the three grade levels. The absence of phonological priming effects in the PDlarge condition is obviously not in line with our hypothesis and also diverges from our previous findings in adults, who did clearly benefit from phonological facilitation in the

PDlarge condition. This indicates that in adults strong phonological contrasts are a prerequisite to separate orthographic from phonological influences, but when phonological contrasts are large enough, orthographic and phonological code activation appear to follow distinct time courses. In contrast, in children, phonological code activation does not become observable, even with the use of strong phonological contrasts.

General discussion

We performed two studies to examine the time course of orthographic and phonological code activation in children at incremental levels of reading proficiency. The first study showed clear orthographic priming effects in children from 2^{nd} grade onwards. With increasing levels of reading proficiency, orthographic priming became facilitative at increasingly short durations. Unexpectedly, phonological priming effects were absent. We reasoned that this absence might have been due to the small phonological differences in the first study. However, the second study, in which phonological difference was manipulated, yielded a similar pattern of results. Contrary to our previous finding in adults (Zeguers et al., 2014), phonological priming was absent in children, even with the use of stimuli with large phonological differences.

The main finding of orthographic priming effects at increasingly early durations, indicates that orthographic codes become increasingly early accessible during reading development. This is in line with both the lexical-quality hypothesis (Perfetti, 2007; Perfetti & Hart, 2002) and dual-route models of reading (Coltheart et al., 2001; Grainger & Ziegler, 2011), but does not seem to square with the lexical tuning hypothesis (Castles et al., 1999, 2007). With respect to the lexical-quality hypothesis, our finding supports the assumption that lexical retrieval becomes increasingly efficient when reading skill increases. With respect to dual-route models, our finding is in agreement with the assumption of increased use of quick, parallel orthographic activation during reading development. However, the lexical tuning hypothesis assumes reduced sensitivity to similar-yet-different prime words during reading development. In contrast, our results seem to indicate that children become more sensitive to primes when reading skill increases, as they benefit from these primes at increasingly short presentation durations

The second finding, the absence of phonological priming effects in developing readers, even with large phonological differences, is in line with dual-route models of reading (Coltheart, 1993; 2001). These models assume that phonological recoding is a laborious, slow process that does not yet occur during the initial stages of the word recognition process. Note, however, that although our findings on phonological priming in children are conform predictions from dual-route models, our findings in adults do not. That is, dual-route models assume that phonological recoding remains slow even when high proficiency in reading skill is achieved, since phonological recoding occurs only when direct orthographic access does not succeed in retrieving the correct lexical representation. In contrast with this latter assumption, adult readers do show phonological priming effects, indicating that in proficient readers, phonological information does become quickly available (Zeguers et al., 2014; and see Ferrand & Grainger, 1992; 1993; 1994; Frost, 2003; Lukatela & Turvey, 1994a; 1994b; Rastle & Brysbaert, 2006 for similar findings of phonological priming effects in skilled readers). Our findings thus rather suggest that phonological processes are not yet automatized in 2nd to 6th grade readers, and that automatic phonological processing emerges later in development. The significant phonological priming effect at the longest exposure duration (83 ms) in the most advanced developing readers (grade 6) in Study 2 supports this hypothesis. In line with this reasoning, the development of automatized reading has been shown to endure well beyond elementary school (Froyen, Bonte, van Atteveld & Blomert, 2009).

Interestingly, if phonological codes are indeed not yet accessed automatically in developing readers, then this also entails that the orthographic priming effects that are present in Study 1 and the PDsmall condition of Study 2 do not reflect combined orthographic and phonological influences, but are manifestations of orthographic processing. This would indicate that orthographic codes are already automatically available in second grade readers and become increasingly automatized throughout elementary school. In contrast, the coupling to corresponding phonological codes does not yet reach the stage of automaticity in grade six. In support of this assumption previous studies have also reported orthographic priming effects in the absence of phonological priming effects in developing readers (Comesaňa et al., 2016; Davis et al., 1998;).

Alternatively, the absence of phonological priming effects may have resulted from the low pre-training familiarity of the participating children with the PDlarge targets. That is, research with pseudoword targets showed that priming effects are absent for words that have no representations in the lexicon (Ferrand, Grainger & Segui, 1994, Forster & Davis, 1984; Forster, Davis, Schoknecht & Carter, 1987; Rajaram & Neely, 1992; but see Bodner & Masson, 1997). Results on the word-reading task indicated that most target items were well learned by the vast majority of the participants. Nevertheless, it is certainly possible that the four week training period was not long enough to build automatized representations and hence representations could not be activated quickly within the first 83 ms of the word recognition process.

One might question whether the absent phonological priming effects are due to insufficient sensitivity of the study's design. The go/no go version of the lexical decision task and the sandwich priming technique have been suggested to enhance sensitivity (Lupker & Davis, 2009; Perea, Jiménez & Gomez, 2015; Perea, Soares & Comesaňa, 2013). However, in a recent study that adopted both the go/no go version of the lexical decision task and the sandwich priming technique, phonological priming effects were also absent in developing readers (Comesaňa et al., 2016).

A few findings require further clarification. First, the absence of consistent orthographic priming effects in the PDlarge condition of Study 2 contrasts with the clear orthographic priming effects in all age groups in the PDsmall condition. This indicates that although children are able to access orthographic codes automatically, they cannot do so with the PDlarge stimuli. Since the orthographic overlap between orthographic primes and targets is generally larger in the PDsmall condition (e.g. *VRIEND-vrienk*) than in the PDlarge condition (e.g. *GOUD– geuf*), it is well possible that the orthographic overlap in the PDlarge condition is simply too small to provide effective facilitation in word recognition.

Second, despite the strong resemblance between the results in Study 1 and the PDsmall condition of Study 2, small differences exist. Most notably, across grade levels, orthographic priming effects arose earlier in Study 2 than in Study 1. Since we found the same effect in a related study with adults (Zeguers et al., 2014), it suggests that the stimulus set of Study 2 was more sensitive. This might have resulted from enhanced matching of the lexical characteristics of stimuli between conditions.

Third, children from grade 2 and 4 appeared to show an identical timing of orthographic priming effects, whereas priming effects emerge earlier in children from grade 6. This suggests that after grade 4, the reading process experiences a developmental leap, which advances the speed of access to orthographic representations. Interestingly, in the Netherlands the end of grade 4 is the time when average readers are considered to reach the level of 'functional literacy' (Verhoeven, 1992). Functional literacy allows children to read various kinds of printed language in daily situations, resulting in a rapid increase in reading practice.

Fourth, we assumed that the orthographic priming effects in Study 1 and the PDsmall condition of Study 2 were manifestations of orthographic processing. However, if the subtle phonological manipulations in these studies have resulted in combined orthographic and phonological influences, as suggested in the adult study, it could be argued that conclusions about isolated orthographic processes are impossible. However, in visual word recognition, orthographic codes are inherently activated before phonological codes (Carreiras, Perea, Vergara & Pollatsek, 2009; Ferrand & Grainger, 1992; 1993; Grainger, Kiyonaga & Holcomb, 2006). Therefore, the earliest subcomponents can be assumed to be orthographic in nature. This leaves the conclusion that orthographic representations become increasingly early accessible when children become more fluent readers intact.

In conclusion, the current study extends our understanding of the important, yet relatively little investigated, stage of reading development following the acquisition of accurate decoding skills. This stage entails the fine-tuning of reading processes into a fluent, rapid and flexible word recognition system. Time course analyses of priming effects suggest that access to orthographic representations become increasingly early available when children become more fluent readers. This supports the notion that reading fluency develops long after the initial reading stage, and indicates that this development of reading fluency is accompanied by enhanced automatisation of orthographic representations.

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Chapter 4

Specifying theories of developmental dyslexia: A diffusion model analysis of word recognition

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Abstract

The nature of word recognition difficulties in developmental dyslexia is still a topic of controversy. We investigated the contribution of phonological processing deficits and uncertainty to the word recognition difficulties of dyslexic children by mathematical diffusion modeling of visual and auditory lexical decision data. The first study showed that poor visual lexical decision performance of reading disabled children was mainly due to a delay in the evaluation of word characteristics, suggesting impaired phonological processing. The adoption of elevated certainty criteria by the disabled readers suggests that uncertainty contributed to the visual word recognition impairments as well. The second study replicated the outcomes for visual lexical decision with formally diagnosed dyslexic children. In addition, during auditory lexical decision, dyslexics presented with reduced accuracy, which also resulted from delayed evaluation of word characteristics. Since orthographic influences are diminished during auditory lexical decision, this strengthens the phonological processing deficit account. Dyslexic children did not adopt heightened certainty criteria during auditory lexical decision, indicating that uncertainty solely impairs reading and not listening.

Introduction

Dysfluent visual word recognition is widely acknowledged as a core characteristic of developmental dyslexia. As a consequence, dyslexic children experience severe impairments in achieving age-appropriate levels of reading. Regarding the exact origin of dyslexics' reading disabilities, controversy still exists (for a discussion see the target article of White et al. (2006) and commentaries of Bishop (2006), Goswami (2006), Nicolson and Fawcett (2006) and Tallal (2006)). In the current study, we address the nature of the word recognition difficulties of dyslexic children by mathematical diffusion modelling of data obtained in visual and auditory lexical decision tasks (Ratcliff & McKoon, 2008; Vandekerckhove & Tuerlinckx, 2007, 2008).

Ìt is now well established that dyslexics' visual word recognition difficulties result from deficits in phonological processing systems (Snowling, 2000; Stanovich, 1988). According to this phonological deficit account, dyslexic children lack awareness of the sound structure of language. As a consequence, they experience difficulties in mapping the orthographic form of words to representations of the corresponding auditory speech sounds and in recalling those representations from memory (Ramus, 2003; Shaywitz & Shaywitz, 2005; Vellutino et al., 2004). Prolonged visual word recognition latencies are considered a behavioral manifestation of these inefficient associations between visual and auditory word characteristics. Phonological difficulties in dyslexic readers are established at different ages (Shaywitz et al., 2007) in different languages (Ziegler & Goswami, 2005) and are supported by neuroimaging studies (Goswami, 2008). However, a different line of research focussed on emotional correlates of dyslexia and shows that reading difficulties often co-occur with reduced self-esteem, heightened levels of stress, worries and uncertainty (Alexander-Passe, 2008; Ingesson, 2007). Academic problems and emotional distress have proven to be mutually reinforcing (Eccles, Wigfield & Schiefele, 1998). Therefore, although emotional problems are initially the consequence of repeated academic failure, it is well possible that, subsequently, emotional problems aggravate the reading difficulties as well. In particular, it has been suggested that extensive worries reduce cognitive processing speed (Eysenck, Derakhshan, Santos & Calvo, 2007). Thus, worries about one's reading ability might reduce speed of visual word recognition in dyslexic children. In the first study we therefore addressed the question whether impaired visual word recognition is solely due to underlying inefficient phonological processes or whether heightened uncertainty aggravates the impairment.

The negative effects of dyslexics' phonological difficulties on visual word recognition are well established. However, phonological processes influence visual word recognition only indirectly, via impaired visual-auditory connections. Auditory language processing tasks, in which the influence of orthographic processes is diminished, may provide a more direct measure of phonological processing and thus allow to study the nature of dyslexics' word recognition difficulties more precisely.

Research aimed at auditory language processing in dyslexic children has increasingly focused on their speech perception abilities. Dyslexic children are believed to be impaired in translating phonetic features of the speech signal into distinct and stable phonological representations (Boets, Ghesquiere, van Wieringen & Wouters, 2007; McBride-Chang, 1995; Ziegler, Pech-Georgel, George & Lorenzi, 2009). These impairments become apparent when speech is perceived in background noise. So-called speech-in-noise perception difficulties have been established in preschoolers at risk for dyslexia (Boets et al., 2007) and in school age children with a diagnosis of dyslexia (Ziegler et al., 2009). Moreover, children with language learning disabilities show anomalous neurophysiological responses to speech stimuli embedded in background noise (Wible, Nicol & Kraus, 2002). Since speech perception relies primarily on auditory language processing, phonetic-phonological associations are crucial to achieve word recognition. The orthographic-phonological associations that are essential in visual word recognition are not a prerequisite for word recognition in the auditory domain. As a consequence, possible effects of orthographic processing on word recognition are diminished in this paradigm and phonological processes are tapped more directly. Therefore, in a second study, we replicated the visual word recognition task and added an auditory word recognition task. We specifically tested whether dyslexic children were impaired on this task as well, and whether the same underlying processes, inefficient phonological processing and increased uncertainty could be demonstrated. As dyslexic children have no history of listening failure, we did not predict heightened uncertainty.

The visual lexical decision task is one of the most often used paradigms in research on the word recognition skills of dyslexic children. It involves the successive presentation of letter strings, and after each letter string children are asked to decide whether the letters form an existing word or not. The word recognition impairments of dyslexic children have been consistently manifested in this task (e.g., Arduino, Burani & Vallar 2003; Nicolson & Fawcett, 1994; Olson, Forsberg, Wise & Rack, 1994). Therefore, we used this task to specify underlying aspects of word recognition impairments. The auditory lexical decision task provides a more direct measure of phonological processing, since orthographic influences are diminished. To assess whether the same underlying processes are involved in visual and auditory word recognition, the auditory lexical decision task in this study was similar to the visual lexical decision task except that stimuli were auditory and presented in noise. We used speech-perception-in-noise since it taps the auditory language processes that are assumed to be impaired in dyslexic children (Bradlow, Kraus & Hayes, 2003; Brady, Shankweiler & Mann, 1983; Ziegler, Pech-Georgel, George, Alario & Lorenzi, 2005).

Computational modelling of reading processes has proven to be very beneficial (Harm & Seidenberg, 1999; Ziegler, Castel, Pech-Georgel, George, Alario & Perry, 2008; Ziegler, Grainger & Brysbaert, 2010). The explicitness of such models encourages formulation of detailed hypotheses. In addition, computational models offer the possibility to discover latent aspects of the reading process that remain hidden in behavioral measures (Ziegler et al., 2008). So far, most theories and models that have been put forward to explain the word recognition deficits in developmental dyslexia are descriptive in nature. In the present study, we will model visual and auditory lexical decision data with the diffusion model. The model has already proven its utility in the study of word recognition processes in normal readers and readers suffering from acquired reading impairments (Ratcliff, Gomez & McKoon, 2004; Ratcliff, Perea, Coleangelo & Buchanan, 2004). The diffusion model offers three advantages. First, it fits data from visual lexical decision tasks very well (Ratcliff, Gomez & McKoon, 2004). Second, the model provides a solution to the so-called 'core problem of two-alternative reaction time tasks' (Wagenmakers, van der Maas & Grasman, 2007). That is, standard analyses deal with measures of speed and accuracy separately, whereas both should be combined to get a complete picture of subject ability. The diffusion model includes measures of speed and accuracy in a single analysis, resulting in one comprehensive view of proficiency in word recognition. Third, the diffusion model yields estimates of latent psychological processes underlying lexical decision performance, the most important ones being drift rate, boundary separation and non-decision time[1]. According to the diffusion model (cf. Figure 1), lexical decisions result from the accumulation of noisy information about the letter string towards one of two boundaries associated with a word or a nonword response (Ratcliff & McKoon, 2008). This information is extracted from lexical characteristics of the letter string, including phonological, orthographic and semantic properties (Ratcliff, Gomez, & McKoon, 2004). Drift rate is defined as the rate at which this information accumulates and is determined by the quality of the evidence about how wordlike a stimulus is. Boundary separation reflects the distance between bounds. It is determined by the amount of evidence needed before a decision is made, and can thus be interpreted as a certainty criterion. Non-decision time consists of all processes other than the decision process, including encoding and response execution. Contrary to some other computational models, the diffusion model does not aim to specify a temporal sequence of processes in word recognition nor does it make predictions about lexical representations in memory (Wagenmakers, Ratcliff, Gomez & McKoon, 2008). Rather, the model distinguishes between latent psychological processes that individually affect the decision processes that are central in a common measure of word recognition, lexical decision.

Previous diffusion model studies have made apparent that boundary separation can be affected independent from drift rate. For example, the age-related slowdown in senescence on a wide range of cognitive tasks is almost entirely related to increases in boundary separation, with drift rates remaining nearly intact (e.g. Ratcliff, Thapar, & McKoon, 2006a; 2006b). Equally, and more directly related to the current study, the poor lexical decision performance of adults with acquired dyslexia is primarily accounted for by increases in boundary separation and non-decision time, with drift rates being hardly impaired (Ratcliff, Perea, Colangelo & Buchanan, 2004).

[1] The other parameters included in the diffusion model are: Starting point, Variability in starting point across trials, Variability in non-decision component across trials and Variability in drift rate across trials (see Ratcliff et al., 2004).

The aim of the current study is to investigate which diffusion model parameters are affected in dyslexic children during visual and auditory lexical decision. Our hypotheses are twofold. First, in the visual lexical decision task we expect that dyslexic children are characterised by lower drift rates and increased boundary separations. Orthographic-phonological processes, the assumed core of dyslexics' impairments, contribute to the decision process in which information about word characteristics is extracted. This process is reflected in the drift rate. In addition, increased boundary separations are expected as a result of the heightened feelings of uncertainty that dyslexics experience due to repeated academic failure. Second, since auditory word recognition taps phonological processing more directly, dyslexic children are expected to show lower drift rates on the auditory lexical decision task as well. That is, the phonetic-phonological processes that are assumed to be impaired in dyslexics, contribute to the decision process based on extraction of word characteristics and are thus reflected in the drift rate. On the auditory task, dyslexics are expected to have unaffected boundary separations since they do not have a history of failure in listening and thus have no reason to be uncertain about their performance on this task. On both the visual and auditory lexical decision task, the nondecision times of dyslexic children are expected to be unimpaired. On the basis of the phonological deficit account, the word recognition deficits of dyslexic children are assumed to lie in language specific processes and do not extend to broader functioning in the areas of perception or motor processes.

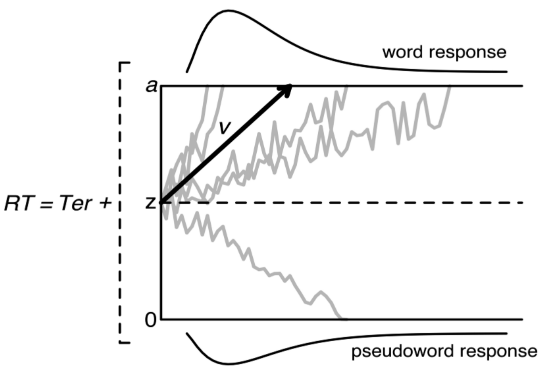

Figure 1. Illustration of the diffusion model in lexical decision. The accumulation of information that drives the decision-making process begins from a startingpoint (z). It continues over time until it reaches either the upper threshold, associated with a 'word'-response (a), or the lower threshold, that is associated with a 'nonword'-response (0). Each erratic line represents the process of information accumulation for a single stimulus letter string. The drift rate (v) is the average rate of information accumulation towards one threshold. The boundary separation (a) describes the distance between thresholds and is determined by the amount of information needed before a decision is made. The non-decision component (Ter) consists of all the processes other than the decision process that are included in the reaction time (RT).

Study 1: Visual lexical decision

Method

Participants

Fifty-seven children with reading disabilities (34 boys, 23 girls) and 57 nonimpaired readers (27 boys, 30 girls) took part in the study. The children attended fourth grade and their age ranged from 9;6 to 11;6 years. None of the children had problems in hearing, vision or attention nor presented with any other form of neurological disability.

Screening

The participants were selected from a sample of 562 children. All parents had provided written informed consent for participation. Selection was based on performance on three screening measures: word reading ability, vocabulary and nonverbal reasoning. Word reading ability constituted the criterion to assign children to the reading ability groups and was measured with the One Minute reading test (*Eén Minuut Test*;, Brus & Voeten, 1979; r = .92 - .94). The group of reading disabled children scored at least 1 standard deviation below the mean for their age group (Z ≤ -1), whereas the children in the typical reading control group had average to above average reading scores (Z = -0.25 to 1.25). Vocabulary and non-verbal intelligence were assessed to rule out the possibility that word reading impairments were due to inadequate vocabulary or intelligence. Vocabulary was assessed with the subtest Vocabulary (*Woordenschat*) of the Amsterdam Child Intelligence Test Battery (*Revisie Amsterdamse Kinder Intelligentietest,* Bleichrodt, Drenth, Zaal & Resing, 1978; r = .81), non-verbal intelligence was measured with the RAVEN Standard Progressive Matrices (Raven, 1958; r = .83). Children were selected when they scored higher than 1 standard deviation below the total sample mean on both the tests of vocabulary and non-verbal intelligence.

Assessment of phonological processing

Children with dyslexia are characterized by phonological processing deficits (Ramus, 2003). Therefore, after establishing deficits in word reading ability in the group of reading disabled children, the presence of dyslexic characteristics was corroborated with measures of phonological processing. Phonological processing can be operationalised through three manifestations: phoneme awareness, verbal short-term memory and speed of accessing verbal codes (Galaburda, LoTurco, Ramus, Fitch & Rosen, 2006; Wagner & Torgesen, 1987). However, in more shallow orthographies such as Dutch, phoneme awareness is acquired rapidly amongst both typical reading and dyslexic children. For this reason, phoneme awareness has proven to be no longer discriminative for dyslexia after the second year of reading instruction in the Netherlands (de Jong & van der Leij, 2002). Therefore, in the first study we used verbal short-term memory and naming speed tasks to assess group differences in phonological processing. Verbal short-term memory was assessed with the subtest Digit Span of the Wechsler Intelligence Scale for Children, Third Edition (WISC-III-NL; r = .66 - .78) (Kort et al., 2002). To measure naming speed, the subtests Letters and Digits of the rapid naming task Test of Continuous Naming and Word Reading (van den Bos, Zijlstra, &

Spelberg, 2002; r = .83 for Letters and r = .86 for Digits) were administered, since these subtests have proven to discriminate dyslexics from nondisabled readers most reliably (Wolf et al., 2002).

Materials

The stimulus set of the lexical decision task consisted of 80 words and 80 pseudowords and was used previously in a study by Martens and de Jong (2006). Words varied in length from three to six letters. The pseudowords were constructed by Martens and de Jong by changing one or two adjacent letters at either the beginning or end of the words. Letters that were replaced within a given word were interchanged with letters of another word. This procedure preserved the consonant-vowel structure of every word in the accessory pseudoword. The pseudowords did not differ significantly from the words in mean bigram frequency.

The stimulus set of 80 words and 80 pseudowords was randomly divided into four subsets of 20 words and 20 pseudowords. This procedure was conducted three times, creating a total of 12 subsets. Each pseudoword was presented in a different subset than the word it was derived from so that no subset contained both a word and its derivate pseudoword. Fourty-item subsets were chosen since a pilot indicated that such duration was within the attentional limits of fourth graders. Within every subset, words and pseudowords had equal numbers of items from each wordlength category and items were presented in randomized order. Each child was presented with all 12 subsets, comprising a total of 480 items, in the same order. Additionally, 10 words and 10 derivate pseudowords were generated to serve as practice trials.

Procedure

The lexical decision task was presented on four identical 15- inch Acer Travelmate 4150 laptops, running Presentation. The task was presented in 16-point Courier font, in black letters on a white background. Letters were 4 mm in length and were presented in uppercase. Children were seated at a viewing distance of 40-60 cm. To assure that every child understood the procedure well, the standardized instruction of the lexical decision task was read aloud by the test assistant and simultaneously presented visually on the computer screen. The task started with 20 practice trials, divided into two blocks. During these practice blocks a well-trained test assistant could check understanding and repeat instructions if necessary. Children were instructed to respond as quickly as possible while making as few errors as possible.

Every trial began with the display of a fixation cross (750 ms). After an interval of 250 ms, the stimulus letter string was presented briefly (120 ms) and followed by a mask of the form ###### (500 ms). Stimulus presentation was limited in order to reduce the chance of errorless performance in the typical reading children, since the diffusion model requires both correct and incorrect responses to adequately fit the data (Voss, Rothermund & Voss, 2004). In addition, the speeded lexical decision task has been shown to be a more sensitive measure of the word reading deficit of dyslexic readers than the regular, unspeeded task (Yap & van der Leij, 1993). The maximum response time was 10 s. Participants responded by pressing one of two pre-allocated black and white colored buttons on the keyboard. The colors were counterbalanced in order to compensate for possible handedness-effects or color associations. Children received no feedback on the accuracy of their responses.

Results

Pre-processing

Seven participants were excluded from the analysis because their datasets contained errors due to technical problems during task administration. Another 16 participants were discarded since the diffusion model did not fit their data. Fits for the diffusion model were assessed for each participant individually by visually comparing the reaction time distribution of the empirical data with the estimated reaction time distribution given the diffusion model parameters. These comparisons were made separately for each of the four conditions: words correct, words incorrect, pseudowords correct and pseudowords incorrect. Participants for whom the estimated reaction time distribution did not follow the empirical reaction time distribution were excluded. This group of 16 excluded participants consisted of 10 children with reading disabilities and 6 nonimpaired readers. Of the remaining participants, practice trials were discharged and data were checked for outliers. For every participant reaction times lower than 250 ms and higher than 3.29 standard deviations above the mean reaction time were removed. On average 3.2% of trials were removed. Of these, 76% were fast responses. For one participant this procedure led to removal of 74% of the trials, which suggested that he had not performed the task seriously and therefore led to exclusion of his data from the sample. This left 90 participants for further analysis, 42 dyslexics (28 boys, 14 girls) and 48 above average readers (23 boys, 25 girls).

Table 1 shows that the two reading groups did not differ significantly on the screening measures of vocabulary ($t(88) = 0.359$; $p = .721$) and nonverbal intelligence ($t(88) = 0.539$; $p = .591$). The reading disabled children did have a significant lower level of word reading ability than the typical readers ($t(88) = 21.831$; $p < .001$, $d = 4.58$). They also performed more poorly on all three measures of phonological processing: Verbal short-term memory ($t(88) = 3.448$; $p = .001$, $d = 0.74$), naming speed for letters ($t(88) = 4.960$; $p < .001$, $d = 1.04$) and naming speed for digits ($t(88) = 5.083$; $p < .001$, $d = 1.07$). In sum, the poor reading of the reading disabled group could not be accounted for by impairments in general cognitive ability or vocabulary, pointing to a disability specific to the process of reading. The deficits in phonological processing indicate the presence of dyslexic characteristics in this group.

Table 1
Results on the screening measures for the children with reading disabilities and nonimpaired readers

	Children with reading disabilities M (SD)	Nonimpaired readers M (SD)	p-value	Cohen's d
N	42	48		
Age (months)	125.26 (5.77)	122.65 (4.06)	.017	0.52
Vocabulary (number of items correct out of 60 items)	50.05 (2.47)	49.85 (2.63)	.721	0.08
Nonverbal Intelligence (number of items correct, out of 48 items)	39.12 (3.32)	39.46 (2.81)	.591	0.11
Technical reading ability (number of items correct, out of 116 items)	45.69 (6.14)	71.29 (4.98)	.000	4.58
Verbal memory (number of items correct, out of 30 items)	11.26 (2.08)	13.02 (2.67)	.001	0.74
Naming speed letters (ms)	29.71 (5.37)	24.60 (4.40)	.000	1.04
Naming speed digits (ms)	29.38 (4.96)	24.50 (4.15)	.000	1.07

Behavioral measures

As expected, the reading disabled children performed worse than the typical readers on the lexical decision task, both on measures of accuracy and reaction time (RT). They had lower accuracy rates (Proportion Correct, PC) than typical readers on both word recognition ($t(88) = 3.089$; $p = .003$, $d = 0.68$) and recognition of pseudowords ($t(88) = 5.323$; $p < .001$, $d = 1.12$). Their RT's were longer than those of their nonimpaired peers, both on word recognition ($t(70.320) = 3.041$, $p = .003$, $d = 0.79$) and recognition of pseudowords ($t(70.403) = 2.978$; $p = .004$, $d = 0.64$). These measures are depicted in Table 2.

Diffusion model analysis

Diffusion model analyses were performed separately for individual subjects with the DMAT software (Vandekerckhove & Tuerlinckx, 2008). In the model, the drift rate parameter was allowed to vary between words and pseudowords. The boundary separation parameter and the non-decision parameter were constrained to be equal for words and pseudowords[2]. Fixation of these parameters over words and pseudowords was based on previous research (Ratcliff et al., 2004a), which indicated that effects of stimulus difficulty, including degree of lexicality, frequency and repetition, does not influence boundary separation nor non-decision time. Diffusion model analyses were executed with word responses at the upper boundary (a) and pseudoword responses at the lower boundary (0) of the diffusion process (see Figure 1). This resulted in positive drift rates for correctly identified words and negative drift rates for correctly identified pseudowords. To enhance comprehensibility of results, signs of the pseudoword driftrates were mirrored after fitting the diffusion model. As a result, both for words and pseudowords positive drift rates indicate correct responses in the current study.

[2] Also all other five diffusion model parameters were fixed across the two lexicality conditions.

Figure 2 shows the concordance between empirical median reaction time and estimated median reaction time for each individual participant. Most values are close to the diagonal, indicating that estimated median reaction times equal their respective empirical median reaction times for almost all participants. As is common in diffusion model analyses of lexical decision data, the largest deviations in model fit are found in the error conditions containing a low number of responses. In our study, the larger deviations represent the error conditions of a few highly accurate participants. As can be seen, overall model fit is acceptable for all included participants.

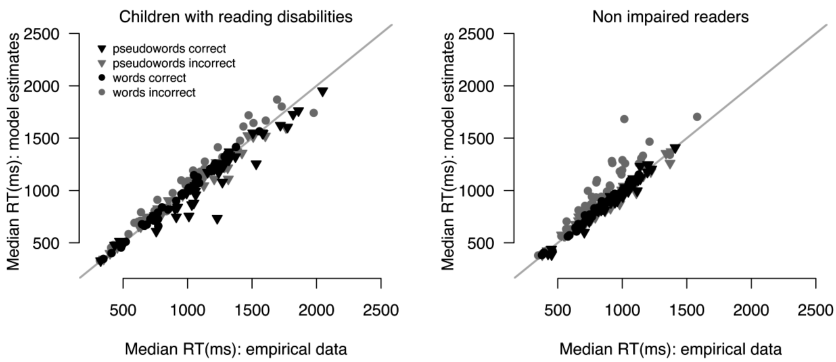

Figure 2. Individual participants' diffusion model fits for Study 1. Model fit is indicated by the concordance between the median reaction time of the empirical data (on the x-axis), and the median reaction time as estimated by the diffusion model (on the y-axis). For each participant and response condition, the distributions of correct responses and errors are represented by single symbols: Triangles indicate pseudowords, bullets indicate words. Gray values indicate error responses, black values indicate correct responses. Model fits are depicted separately for the children with reading disabilities (left panel) and for the nonimpaired readers (right panel).

Diffusion model parameters

The mean estimated diffusion model parameters for both reading ability groups are depicted in Table 2. It shows that children with reading disabilities had lower drift rates than nonimpaired readers, both for words ($t(88) = 3.600$; $p = .001$, $d = 0.98$) and for pseudowords ($t(88) = 4.993$; $p < .001$, $d = 1.06$). In addition, boundary separations were larger for reading disabled children than for children in the typical reading group ($t(88) = 2.195$; $p = .031$, $d = 0.65$). No group differences were found on the non-decision component ($t(67.914) = 0.154$ $p = .878$). Results on the diffusion model parameters are depicted in Table 2.

Table 2
Percentage correct (PC), reaction time (RT) and diffusion model parameters for the children with reading disabilities and nonimpaired readers.

	Children with reading disabilities M (SD)	Nonimpaired readers M (SD)	p-value	Cohen's d
Behavioral Measures				
PC of Words	.80 (.12)	.87 (.08)	.003	0.68
PC of pseudowords	.50 (.15)	.68 (.17)	.000	1.12
RT of words	1170.37 (362.03)	926.50 (242.12)	.003	0.79
RT of pseudowords	1224.40 (390.21)	1012.40 (263.17)	.004	0.64
Diffusion Model Parameters[3]				
Drift rate for words	.150 (.095)	.232 (.118)	.001	0.98
Drift rate for pseudowords	.006 (.119)	.134 (.122)	.000	1.06
Boundary Separation	.191 (.469)	.167 (.054)	.031	0.65
Non-decision Component	.610 (.209)	.604 (.133)	.878	0.03

Discussion

The results of this first study indicate that the diffusion model successfully captures lexical decision data of both reading disabled and typical reading children. The model provides one comprehensive measure of visual word recognition, in which both reaction time and accuracy are taken into account. Behavioral measures replicated findings of earlier studies (e.g. Thaler et al., 2009; Ziegler, Perry, Ma-Wyatt, Ladner & Schulte-Körne, 2003; Zoccolotti et al., 2005) by showing that performance of children with reading disabilities was characterised by both lower accuracy rates and longer response latencies. Application of the diffusion model offered valuable additional information about the deficiencies of children with reading disabilities, thereby providing insights into the nature of their word recognition deficits. Reading disabled children appeared to have substantially lower drift rates than their typical reading peers and, in addition, employed larger boundary separations. They did not present with longer non-decision components of the reaction times. This implies that the impaired visual lexical decision performance of dyslexic readers could be accounted for to a great extent by a diminished speed of gathering information about the word, in which the adoption of elevated certainty criteria exacerbated the deficiency. Aspects of task performance outside the decision-making process did not contribute to the word recognition deficit.

[3] Mean values (standard deviations between brackets) of the four other diffusion model parameters are as follows. For the children with reading disabilities: Starting point: 0.104 (0.029); Variability in starting point: 0.112 (0.073); Variability in non-decision component: 0.473 (0.250); Variability in drift rate: 0.127 (0.129). For the nonimpaired readers: Starting point: 0.098 (0.032); Variability in starting point: 0.103 (0.062); Variability in non-decision component: 0.345 (0.147); Variability in drift rate: 0.140 (0.114).

Since the first application of the diffusion model on dyslexic word recognition processes had proven successful, a second study was performed to explore the nature of dyslexics' deficits in word recognition in more detail. In this second study, three modifications were made. First, the study included children with a formal dyslexia diagnosis to corroborate the findings from the children with reading disabilities in a clinical population. Second, a speech-in-noise perception task was added to the design to investigate whether the lower drift rates that underlie dyslexics' visual word recognition are also present during auditory word recognition, which constitutes a more direct measure of phonological processing. Third, a second control group was added, consisting of younger typical reading children with a reading level comparable to the dyslexics. Inclusion of so-called reading age controls is often advocated in studies involving dyslexic readers to rule out the possibility that differences between dyslexics and same-age typical readers are due to differences in reading experience. That is, when a traditional chronological-age match design establishes deficits in dyslexic children, it is unclear whether these deficits are the cause or the consequence of dyslexics' reading disability (Bryant & Goswami, 1986; van den Broeck, Geudens & van den Bos, 2010). The second study thus included three groups of participants. A group of 4th grade dyslexic readers, a chronological age control group and a reading age control group of 2nd grade typical readers with a reading level comparable to the dyslexics.

Study 2: visual and auditory lexical decision

Method

Participants

In this study, 47 dyslexic children (13 boys, 34 girls) were recruited from two certified dyslexia institutions. All children attended grade 4 and their age ranged between 9;6 and 11;6 years. Prior to recruitment, every child had received a formal diagnosis of dyslexia on the basis of an extensive cognitive psycho-diagnostic assessment in accordance with the Protocol for Diagnosis and Treatment of Dyslexia (Blomert, 2006). Two control groups were selected from the schools of the dyslexic participants. The chronological age control group (CA control group) consisted of 50 grade-4 children (20 boys, 30 girls, age range 9;7-11;4 years) with average or above average reading ability. CA-control children had standard scores (M=10, SD=3) in word reading between 8 and 15. The CA-control group was matched with the dyslexic group on vocabulary and non-verbal intelligence. Vocabulary was assessed with the subtest Vocabulary (*Woordenschat*) of the Amsterdam Child Intelligence Test Battery (*Revisie Amsterdamse Kinder Intelligentietest,* Bleichrodt et al., 1978), non-verbal intelligence was measured with the Raven Standard Progressive Matrices (Raven, 1958). The reading age control group (RA control group) consisted of 36 grade-2 children with average reading ability (13 boys, 23 girls, age range 7;1-8;8 years). This group was matched with the dyslexic group on word reading ability, as assessed with the One Minute Test (*Eén Minuut Test*; Brus & Voeten, 1979). All children attended regular education and were native Dutch speakers without a history of problems in hearing, vision, attention or any other form of neurological disabilities. All parents had provided written informed consent for participation.

Stimulus set

The stimulus set of both the visual and auditory lexical decision task was identical to Study 1. Auditory forms of the stimuli were read by a female Dutch speech therapist in a sound attenuated room and recorded on a solid state recorder, Edirol-R1, at a sampling rate of 44.1 kHz, 16 bits and stored as wave. Natural speech was used in this study to enhance generalisability to everyday listening situations. Previous speech perception experiments have often used synthetic speech, but it has been questioned whether results from these paradigms correspond to dyslexics' speech perception performance under natural listening conditions (Blomert & Mitterer, 2004). The PRAAT software (Boersma & Weenink, 2003) was used to inspect spectrograms of each spoken stimulus and determine stimulus onset and offset. Each stimulus was then extracted from the digital file and saved as an individual file. The mean acoustic duration of word stimuli was 768,18 ms (range 539 - 964) . The pseudoword stimuli had a mean acoustic duration of 775,15 ms (range 536 – 1115). Root mean square amplitudes of all stimuli were rescaled to 65 dB SPL, in order to ensure equality of overall sound levels. Subsequently, the auditory stimuli were consolidated with a noise mask at a 0 dB signal-to-noise ratio (S/N). This S/N ratio was determined on the basis of a pilot study, showing above chance levels of auditory word and nonword recognition in both 4th grade dyslexic children and 2nd grade typical reading children. The noise mask consisted of pink noise with amplitudes of 65 dB and a spectral slope of -6 dB/ octave, since this resembles the intensity and frequency spectrum of speech and thus approximates the effect of natural background noise (comparable to the so-called cocktailparty background noise, Bronkhorst, 2000). The noise mask included all frequencies of a database of the Dutch vocabulary (Corpus Spoken Dutch, Oostdijk, 2002). In this way, the risk of affecting specific phonemes more than others was diminished.

Procedure

The procedure of the visual lexical decision task was identical to Study 1. Although, stimulus duration was extended to 150 ms, since a pilot study indicated this presentation duration suitable for grade-2 children. Visual and auditory lexical tasks were presented on the same laptops. Auditory stimuli were presented binaurally through circumaural headphones (IMG Stageline, MD-5000 DR). The 65dB-intensity of the acoustic output levels was controlled in Presentation. As in the visual task, every trial of the auditory lexical decision task started with the display of a fixation cross on the computer screen (750 ms), followed by a 250-ms interval. Subsequently, the auditory stimulus was presented and the trial ended with a mask (######, displayed for 500 ms). All other aspects of the procedure were identical to the procedure of the visual lexical decision task. In Study 2, the visual lexical decision task was administered before the auditory lexical decision task. This guaranteed identical administration conditions for the visual lexical decision task across the two studies.

Results

Pre-processing

In the second study, exclusion of premature responses (faster than 250 ms) resulted in a removal of 5,3% of trials in the visual task and 2,2% in the auditory task. Seven participants (three CA's and four RA's) were excluded from further analyses because their results suggested they had not responded seriously on either the visual or auditory task. These participants performed at chance level on the word items or showed a response tendency (above 90% of responses on the same button), which indicated guessing behavior. Item-level analyses were conducted to verify whether the items, which were primarily selected for the purpose of a visual lexical decision task with grade-4 children, had been appropriate for use in the auditory task and for grade-2 children. Two items were removed. On one of these items ("bal", meaning "ball"), average performance on the auditory task was on chance level in all groups, whereas average performance for this item on the visual task indicated that the word was well known (PC > .88 in all groups). This suggests that overlap in frequencies of the spectrogram of this item and its noise mask impeded auditory processing. The second excluded item ("vee", meaning "cattle") appeared to be unfamiliar to the grade-2 participants, as indicated by chance-level performance for this group on both the visual and auditory task. For each participant, reaction times exceeding two standard deviations above the mean reaction time were considered outliers and were removed, resulting in removal of 3,8% of trials in the visual task and 4,4% in the auditory task. After application of the diffusion model, nine participants (one dyslexic, seven CA-controls and one RA-control) were excluded from further analyses as a result of inappropriate model fit. The fit of the model was assessed analogously to Study 1. This left 117 participants for further analysis, 46 dyslexics (14 boys, 32 girls), 40 grade-4 typical readers (17 boys, 23 girls) and 31 grade-2 typical readers (11 boys, 20 girls).

As depicted in Table 3, contrast tests in an ANOVA showed that the dyslexic children did not differ from the CA-controls on vocabulary ($t(113) = 1.691$; $p = .094$) and nonverbal intelligence ($t(114) = 1.699$; $p = .092$). The dyslexics did have a significant lower word reading level than the CA-controls ($t(114) = 15.444$; $p < .001$). Results thus indicate that any difference between the dyslexic and CA-group cannot be attributed to effects of vocabulary or nonverbal intelligence. Contrasts between dyslexic readers and RA-controls make apparent that the groups did not differ on word reading ability ($t(114) = 1.818$; $p = .072$). However, results show a trend towards higher word reading ability in the RA-controls. Therefore, in further analyses word reading ability is included as a covariate to rule out the possibility that differences between the dyslexic and RA-group can be attributed to effects of word reading ability Since representative age-corrected norm scores were not available for the measures of vocabulary and nonverbalintelligence, differences between dyslexics and RA-controls on these measures could not be interpreted.

Behavioral measures

Results of the visual lexical decision task are summarized in Table 4. On the visual lexical decision task, dyslexic readers performed worse than CA-controls with respect to both accuracy and response latency. Contrast tests in an ANOVA showed that dyslexics had lower accuracy rates on word recognition ($t(78.097) = 4.342$; $p < .001$, $d = 0.99$) as well as recognition of pseudowords ($t(114) = 6.539$; $p < .001$, $d = 1.59$). Dyslexics' response latencies were longer, both on word recognition ($t(72.709) = 2.614$; $p = .011$, $d = 0.59$) and recognition of pseudowords ($t(77.670) = 2.420$; $p = .018$, $d = 0.55$). An ANCOVA with word reading as a covariate made clear that, in comparison to RA-controls, dyslexic readers did not differ in accuracy on word recognition ($F(1) = 0.068$; $p = .795$) nor on pseudoword recognition ($F(1) = 0.630$; $p = .430$). In contrast, dyslexic readers had shorter average response latencies than RA-controls for both words ($F(1) = 8.713$; $p = .004$, $d = 0.48$) and pseudowords ($F(1) = 7.098$, $p = .009$, $d = 0.39$).

Results on the behavioral measures of the auditory lexical decision task are summarized in Table 5. On the auditory task, the dyslexic children also performed more poorly than CA-controls. Their accuracy rates were lower on both word recognition ($t(114) = 2.769$; $p = .007$, $d = 0.67$) and recognition of pseudowords ($t(114) = 2.931$; $p = .004$, $d = 0.67$). Dyslexics did not differ from CA-controls on response latency, neither for words ($t(114) = 0.295$; $p = .768$) nor pseudowords ($t(114) = 0.566$; $p = .573$). Performance of dyslexic readers was highly similar to that of RA-controls. Dyslexics did not differ from RA-controls in accuracy of word recognition ($F(1) = 1.151$; $p = .287$) nor pseudoword recognition ($F(1) = 0.111$; $p = .740$). The dyslexic readers and RA-controls did also not differ in reaction time for words ($F(1) = 0.996$; $p = .322$) nor for pseudowords ($F(1) = 2.723$, $p = .103$)[4].

[4] In the ANOVA's on the reaction time measures, reading level was not added as a covariate because of a significant interaction between reading level and group, indicating a differential effect of reading level for the dyslexics and RA-controls.

Table 3

Results on the screening measures for the children with dyslexia, the chronological age control group and the reading age control group

	Dys N=46 M (SD)	CA N=40 M (SD)	RA N=31 M (SD)	p-value DYS-CA	p-value DYS-RA	Cohen's d DYS-CA	Cohen's d DYS-RA
Age (months)	124.04 (6.47)	122.93 (4.33)	97.43 (5.41)	.347	.000	0.22	4.44
Technical reading ability (number of items correct, out of 116 items)	43.48 (8.98)	70.55 (8.33)	46.90 (6.23)	.000	.072	4.85	0.76
Vocabulary (number of items correct, out of 60 items)	49.02 (3.35)	50.23 (3.21)	45.10 (3.25)	.094	.000	0.40	1.20
Nonverbal intelligence (number of items correct, out of 60 items)	39.54 (6.00)	41.68 (5.32)	36.52 (6.09)	.092	.027	0.41	0.51

Note: Dys = Children with dyslexia; CA= Chronological age controls; RA= Reading age controls.

Table 4

Percentage correct (PC), reaction time (RT) and diffusion model parameters on the visual lexical decision task for the three reading groups

	Dys N=46 M (SD)	CA N=40 M (SD)	RA N=31 M (SD)	p-value DYS-CA	p-value DYS-RA	Cohen's d DYS-CA	Cohen's d DYS-RA
<u>Behavioral Measures</u>							
PC of Words	.80 (.09)	.87 (.06)	.81 (.10)	.000	.795	0.99	0.10
PC of pseudowords	.48 (.14)	.71 (.16)	.52 (.17)	.000	.430	1.59	0.22
RT of words	985.49 (309.30)	846.19 (174.41)	1142.43 (356.25)	.011	.004	0.59	0.48
RT of pseudowords	1199.96 (405.95)	1024.05 (260.83)	1363.09 (455.01)	.018	.009	0.55	0.39
<u>Diffusion Model Parameters</u>							
Drift rate for words	.139 (.078)	.210 (.083)	.133 (.061)	.000	.621	0.96	0.10
Drift rate for pseudowords	.011 (.081)	.147 (.097)	.017 (.099)	.000	.281	1.84	0.07
Boundary Separation	.184 (.055)	.162 (.054)	.212 (.052)	.057	.005	0.45	0.53
Non-decision Component	.552 (.226)	.557 (.126)	.562 (.270)	.904	.574	0.03	0.04

Note: Dys = Children with dyslexia; CA= Chronological age controls; RA= Reading age controls.

Table 5

Percentage correct (PC), reaction time (RT) and diffusion model parameters on the auditory lexical decision task for the three reading groups

	Dys N=46 M (SD)	CA N=40 M (SD)	RA N=31 M (SD)	p-value DYS-CA	p-value DYS-RA	Cohen's d DYS-CA	Cohen's d DYS-RA
Behavioral Measures							
PC of Words	.85 (.07)	.90 (.06)	.87 (.08)	.007	.287	0.67	0.21
PC of pseudowords	.59 (.15)	.69 (.14)	.58 (.17)	.004	.740	0.67	0.11
RT of words	1347.54 (258.37)	1332.46 (196.40)	1390.74 (248.98)	.768	.322	0.07	0.17
RT of pseudowords	1518.24 (266.86)	1552.90 (294.50)	1645.70 (292.99)	.573	.103	0.12	0.47
Diffusion Model Parameters							
Drift rate for words	.128 (.035)	.178 (.071)	.147 (.086)	.001	.199	0.87	0.32
Drift rate for pseudowords	.049 (.050)	.099 (.060)	.042 (.059)	.000	.994	0.88	0.13
Boundary Separation	.184 (.041)	.184 (.046)	.189 (.035)	.976	.456	0.01	0.15
Non-decision Component	.846 (.139)	.910 (.099)	.906 (.136)	.021	.101	0.54	0.43

Note: Dys = Children with dyslexia; CA= Chronological age controls; RA= Reading age controls.

Diffusion model analysis

Diffusion model analyses were performed analogously to Study 1. Analyses were executed separately for the visual and auditory lexical decision task data. Figure 3 shows the concordance between empirical median reaction time and estimated median reaction time for each individual participant, both for the visual and auditory lexical decision task. Most values are close to the diagonal, indicating that estimated median reaction times equaled their respective empirical median reaction times for almost all participants. As can be seen from Figure 3 overall fits were highly appropriate for all participants on both tasks.

Diffusion model parameters

Diffusion model parameters of the visual lexical decision task are summarized in Table 4. On the visual lexical decision task, diffusion model results correspond well to the results of Study 1. ANOVA contrast tests showed that dyslexic children had lower drift rates than CA-controls, both for words ($t(114) = 4.622$; $p < .001$, $d = 0.96$) and for pseudowords ($t(114) = 7.241$; $p < .001$, $d = 1.84$). Dyslexics and CA-controls did not differ significantly in the width of their boundary separations ($t(114) = 1.921$; $p = .057$). The difference approached significance though, suggesting wider boundary separations in the group of dyslexic children than in the CA-control group. No group differences were found on the non-decision component ($t(68.488) = 0.357$; $p = .722$).
In comparison to RA-controls, dyslexic readers did not differ in drift rate. Neither on word recognition ($F(1) = 0.246$; $p = .621$) nor on pseudoword recognition ($F(1) = 1.478$; $p = .281$). Dyslexic children presented with smaller boundary separations than RA-controls ($F(1) = 8.308$; $p = .005$, $d = 0.53$). The dyslexic and RA-group did not differ in nondecision component ($F(1) = 0.319$; $p = .574$)[5].

Results on the diffusion model parameters of the auditory lexical decision task are summarized in Table 5. On the auditory task, comparisons between dyslexic and CA-controls made apparent that dyslexic children had lower drift rates, both for words ($t(55.942) = 4.292$; $p < .001$, $d = 0.87$) and for pseudowords ($t(114) = 4.344$; $p < .001$, $d = 0.88$). Dyslexics and CA-controls did not differ in boundary separation (t(114) = 0,092;

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[5] Mean values (standard deviations between brackets) of the four other diffusion model parameters are as follows. For the children with dyslexia: Starting point: 0.103 (0.028); Variability in starting point: 0.109 (0.079); Variability in non-decision component: 0.512 (0.344); Variability in drift rate: 0.105 (0.108). For the chronological age controls (CA): Starting point: 0.093 (0.031); Variability in starting point: 0.106 (0.066); Variability in non-decision component: 0.411 (0.203); Variability in drift rate: 0.069 (0.055). For the reading age controls (RA): Starting point: 0.116 (0.026); Variability in starting point: 0.117 (0.086); Variability in non-decision component: 0.563 (0.395); Variability in drift rate: 0.105 (0.111).

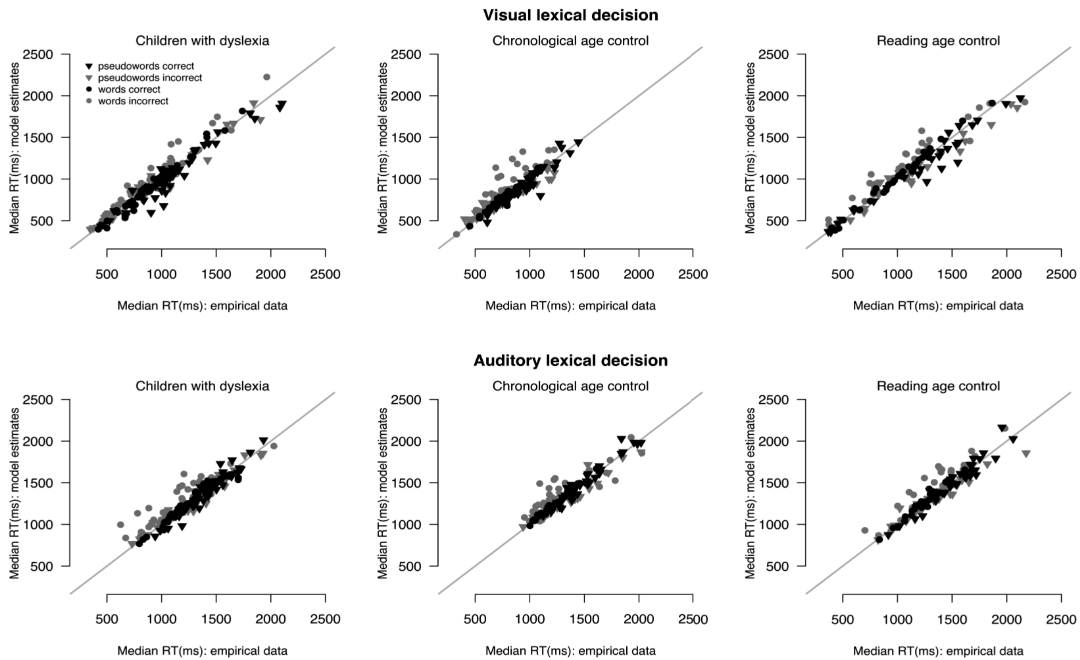

Figure 3. Individual participants' diffusion model fits for Study 2. Model fit is indicated by the concordance between the median reaction time of the empirical data (on the x-axis), and the median reaction time as estimated by the diffusion model (on the y-axis). For each participant and response condition, the distributions of correct responses and errors are represented by single symbols: Triangles indicate pseudowords, bullets indicate words. Gray values indicate error responses, black values indicate correct responses. Model fits are depicted separately for the children with dyslexia (left panel), for the children in the chronological age control group (middle panel) and for the children in the reading age control group (right panel).

p = .927). Dyslexics did however present with shorter nondecision components (t(114) = 2.452; *p* = .016, *d* = 0.54*).* In comparison to RA-controls, dyslexic readers did not differ in drift rate for word recognition (F(1) = 1.679; *p* = .199) nor for pseudoword recognition (F(1) = 0.000; *p* = .994). There were neither group differences on boundary separation (F(1) = 0.561; *p* = .456) nor on the nondecision component (F(1) = 2.764; *p* = .101)[6].

Discussion

In the second study, results on the visual lexical decision task replicated the findings of the first study. This indicates that the findings of Study 1 generalise well to a clinical population of formally diagnosed dyslexic children. On the behavioral measures, dyslexics presented once again with both longer response latencies and lower accuracy rates in comparison to CA-controls. Diffusion model analyses showed, as in the first study, lower drift rates and a trend towards wider boundary separations, but equally large non decision components for the dyslexics when compared to CA-controls.

In comparison to the RA-controls, dyslexic readers presented with comparable accuracy rates for both words and pseudowords. However, both words and pseudowords were recognized faster by the dyslexics. This suggests that oral reading, the measure on which dyslexics and RA-controls were matched, might be more impaired in dyslexic readers than silent reading. Previous research corroborates this finding by showing that dyslexics have more difficulties with tasks that require overt pronunciation of pseudowords than with tasks that rely on implicit decoding only (Stanovich & Siegler, 1994). Diffusion model analyses made apparent that the dyslexic and RA-controls did not differ with respect to drift rate or non decision component. However, RA-controls had wider boundary separations than the dyslexic children.

Results thus indicate that dyslexics show slow and inaccurate visual word recognition in comparison to CA-controls. These word recognition difficulties can be accounted for by a lower speed of gathering information about stimulus words (i.e. drift rate) and the adoption of higher certainty criteria (boundary separation) in comparison to CA-controls. Dyslexics did not, however, require more time for processes outside the decision process. Comparisons between dyslexics and RA-controls indicated that, although dyslexics could recognize both words and pseudowords faster than RA-controls, their rate of information gathering about stimulus words was similar. The dyslexics and RA-controls did also employ comparable time

[6] Mean values (standard deviations between brackets) of the four other diffusion model parameters are as follows. For the children with dyslexia: Starting point: 0.101(0.022); Variability in starting point: 0.111 (0.063); Variability in non-decision component: 0.674 (0.330); Variability in drift rate: 0.041 (0.056). For the chronological age controls (CA): Starting point: 0.105 (0.027); Variability in starting point: 0.088 (0.068); Variability in non-decision component: 0.504 (0.242); Variability in drift rate: 0.070 (0.060). For the reading age controls (RA): Starting point: 0.111 (0.025); Variability in starting point: 0.092 (0.061); Variability in non-decision component: 0.570 (0.212); Variability in drift rate: 0.060 (0.055).

for non-decision processes. However, the RA-controls had even higher decision criteria than the dyslexics, indicating a need for more certainty before they made a response. The dyslexics' advantage in word recognition rate thus seems to result from higher certainty levels during visual lexical decision amongst the dyslexic children than the younger RA-controls. This is in line with the finding that, in children, boundary separations decrease during maturation (Ratcliff, Love, Thompson, & Opfer, 2012).

On the auditory lexical decision task, behavioral measures showed lower accuracy rates and similar response latencies for the dyslexic children in comparison to CA-controls. Diffusion model analyses of these results supported our hypothesis with respect to auditory word recognition. That is, as in the visual lexical decision task, the reduced accuracy amongst the dyslexic readers could be attributed to prolonged drift rates in comparison to CA-controls. However, there was no difference with respect to boundary separation on the auditory task. This suggests that in contrast to the visual lexical decision task, dyslexic children do not need to be more certain before making a decision during auditory word recognition. Contrary to expectations, dyslexic readers showed shorter non decision components than CA-controls, indicating faster non-decision related processes.

Reading level match comparisons in the auditory task yielded highly similar results for the dyslexic readers and RA-controls. On the behavioral measures, dyslexic children presented with comparable accuracy rates and reaction times, both for words and pseudowords. Diffusion model analyses indicated comparable drift rates, boundary separations and nondecision components in both groups.

General discussion

In congruence with several previous studies (e.g. Thaler et al., 2009; Ziegler et al., 2003; Zoccolotti et al., 2005) the current study shows that dyslexics' visual word recognition processes are both slow and inaccurate in comparison to same-age typical readers. Application of the diffusion model offered valuable additional information about dyslexics' deficiencies beyond response latency and accuracy, thereby providing insight into the nature of the word recognition deficits. Results show that dyslexics' visual lexical decision difficulties, a core characteristic of developmental dyslexia, can be accounted for primarily by a delay in the linguistic decision processes in which information about word characteristics is extracted. These decision processes involve phonological processes in addition to orthographic and semantic processes. The difficulties in visual lexical decision appear to be exacerbated by the adoption of elevated certainty criteria, indicating that heightened uncertainty hampers dyslexic children in their word recognition performance as well.

The current study also contributes to the growing evidence of auditory language processing difficulties in dyslexic children. That is, although dyslexic children could auditorily recognize words as fast as their typical reading classmates, their accuracy was diminished. Diffusion model analyses established that dyslexics' auditory word recognition difficulties are, analogous to their visual word recognition difficulties, primarily the result of delays in the evaluation of word characteristics. In auditory word recognition, as is the case in visual word recognition, these decision processes depend on phonological and semantic processes. However, contrary to visual lexical decision, auditory word recognition does not necessarily rely on orthographic processing whereas phonological processing is essential. In contrast to visual word recognition, in the auditory domain dyslexics' word recognition is not hampered by elevated certainty criteria, indicating that uncertainty does not play a role.

With respect to visual word recognition, our results thus suggest that dyslexics' inefficient visual word recognition results primarily from a core delay in the evaluation of word characteristics. This is in line with the phonological deficit hypothesis. However, the elevated certainty criteria amongst dyslexic children suggest an additional effect of heightened feelings of uncertainty and indecisiveness on dyslexics' visual word identification skills. Since dyslexics' certainty criteria are not elevated during auditory lexical decision, their uncertainty seems to be specifically related to reading. This corresponds with the assumption that the uncertainty of dyslexic children is related to the academic failure that they have experienced repeatedly in reading and not in listening. Although there is substantial evidence showing that dyslexics experience feelings of uncertainty (Alexander-Passe, 2008; Ingesson, 2007; Morgan, Farkas, Tufis & Sperling, 2008), the findings from the current diffusion model analyses indicate that uncertainty has a direct influence on dyslexics' performance on visual lexical decision tasks. Heightened uncertainty has only received relatively limited attention. However, the current results warrant further investigation of the relation between reading disability and uncertinty.

It might be argued that, apart from effects on drift rate, dyslexics' deficits in phonological processing affect encoding as well during visual word recognition, in the form of basic letter-sound mappings. This should result in lengthened nondecision times. However, the present results do not support this idea since the nondecision component did not differ between dyslexic children and their nonimpaired class mates.

Regarding auditory word recognition, results indicate that the phonological deficit of dyslexic children is also related to auditory language processing. Dyslexics' inaccurate auditory word recognition stems primarily from a delay in the evaluation of auditory word characteristics, in which phonetic-phonological associations play a central role. The finding of lower drift rates in both visual and auditory word recognition provides further support for the phonological deficit hypothesis. That is, both in visual and auditory word recognition the primary delay seems to reside in the processes in which information about different word characteristics is extracted, interpreted and combined. The nature of the specific word characteristics that are extracted differs between the two types of word recognition. Visual word recognition depends more heavily on orthographic cues, whereas auditory word recognition relies principally on auditory cues, amongst which are acoustic and phonetic features. Since the processes of evaluating word characteristics are impaired in both visual word recognition, which is generally agreed to reflect the dyslexic deficit, and in auditory word recognition, in which orthographic influences are diminished, this supports the assumption that the core problem resides in the word characteristics essential for both visual and auditory word recognition, that is, in phonological processes.

Comparisons to reading age controls did not replicate the deficiencies in behavioral word recognition measures nor the decreases in drift rates that were found in the chronological age level comparisons. Dyslexics and younger typical readers performed highly similar in auditory word recognition, both on behavioral and diffusion model measures. In visual word recognition, dyslexics could recognize both words and pseudowords equally accurate yet faster than the younger typical readers with whom they were matched on oral word reading level. The reading speed advantage of the dyslexics appeared not to result from increased proficiency in the processes in which word characteristics are evaluated, as both groups presented with similar drift rates. Rather, the dyslexics benefitted from lower levels of uncertainty, which manifested in smaller boundary separations.

The absence of deficiencies in the reading age control comparisons could be interpreted to indicate that dyslexics' difficulties in word recognition and the underlying impairments in the processes in which word characteristics are evaluated, do not constitute qualitative processing deficits, but are better interpreted as a developmental delay resulting from a lack of reading experience (Backman, Mamen & Ferguson, 1984). However, several authors have argued that one should be careful in interpreting results from reading level match comparisons (Goswami & Bryant, 1989; Van den Broek et al., 2010). That is, the dyslexic and younger typical reading children are solely matched on word reading ability. This leaves open a multitude of other variables on which the groups are not matched and which could thus differently influence performance in the two groups. Amongst these, age-related variables are the most plausible to influence word recognition performance, and these include orthographic and semantic knowledge, exposure to spoken language, and metacognition. Therefore, one cannot rule out the possibility that dyslexics do experience a processing deficit in comparison to the younger typical readers, but can compensate for this deficit by means of their maturational advantage.

The claim that the dyslexic and younger typical readers take qualitatively different courses to achieve word recognition is supported by the group differences on visual lexical decision. That is, dyslexic children and younger typical readers did achieve similar drift rates, but the younger readers adopted a more conservative decision style which resulted in lower eventual word recognition rates. Although an age-related decrease in certainty thresholds is in line with previous findings (Ratcliff, Love, Thompson & Opfer, 2012), it is unlikely that these group differences can be accounted for by a general inclination to become more liberal in decision making during maturation. Namely, if this were the case, the 2nd grade typical readers would be expected to set higher certainty criteria than the 4th grade dyslexic children in the auditory lexical decision task as well. It thus seems more plausible that the heightened uncertainty of the 2nd grade readers is specific to reading, possibly due to less experience with speeded reading. That is, in the Netherlands, speeded word reading from a computer screen (flashcard reading) is a common used technique in remediation programs for dyslexic children. The dyslexic children in the current study can thus be expected to have practised extensively with speeded reading, whereas the 2nd grade typical readers, who attend regular curricula, have generally had far less experience with this type of reading. Interestingly, despite the extensive practice with speeded reading, dyslexic children were more conservative than chronological age controls who are also not accustomed to such an approach. This strengthens our previous claim that dyslexics' repeated academic failure in reading may account for their uncertainty. The contrast between the performance of the dyslexics and 2nd graders on visual and oral word reading needs further discussion. During visual word recognition, dyslexic readers could benefit from relatively low uncertainty levels to achieve a reading speed advantage in comparison to the younger typical readers. However, they did not show this advantage during the screening measure of oral word reading. This suggests that during oral reading, dyslexics are either even more hampered by uncertainty than during silent reading, or experience such severe impairments in the evaluation of word characteristics that they can't be compensated for by reduced uncertainty. Since both silent reading and reading aloud take a prominent position in education, future studies may explore the differential effects of uncertainty in the two types of reading.

With respect to the nondecision component, the similarity between the dyslexic readers and both control groups during visual word recognition confirms that non-language related processes are not impaired in dyslexics during silent reading (Ziegler, Pech-Georgel, Dufau & Grainger, 2010). During auditory word recognition, dyslexics' nondecision components were also similar to younger children with comparable reading levels. However, in this auditory task, dyslexics presented with shorter non decision components than same age typical readers. This finding needs to be replicated in future studies and also calls for further study of the nondecision component. A valuable first attempt to improve interpretability of this component has recently been made (Voss, Voss & Klauer, 2010).

In this first application of the diffusion model in the field of developmental dyslexia, the model has proven capable of providing valuable additional information about dyslexics' deficiencies, beyond response latency and accuracy. Binary decision tasks are a frequently used method in research on reading disabilities, and the diffusion model provides a powerful tool to extend the information that can be acquired from these tasks, more specifically to disentangle effects of word evaluation processes from uncertainty. Future applications of the diffusion model to developmental dyslexia might further enhance our understanding of dyslexics' deficit. First, diffusion model analyses can investigate age related changes in uncertainty. Second, the diffusion model can be applied at the level of individual dyslexic children to account for individual differences in underlying deficits (Ziegler et al., 2008). Third, the diffusion model can be used to evaluate treatment effectiveness. This may clarify to what degree particular interventions (e.g. Snellings, van der Leij, de Jong & Blok, 2009;

Tan & Nicholson, 1997; Thaler, Ebner, Wimmer & Landerl, 2004) affect drift rate and boundary separation, and thereby decompose intervention effects into those related to changes in core processes involved in visual word recognition and those related to changes in confidence/uncertainty levels.

In conclusion, the diffusion model has proven to be highly valuable in investigating the nature of word recognition deficits amongst dyslexic children. Results indicate that difficulties in both visual and auditory word recognition can be traced back to deficits in the processes in which word characteristics are evaluated. This supports the assumption that a phonological deficit constitutes the primary cause of dyslexics' impairments in reading as well as speech perception. Results also warrant attentiveness to heightened feelings of uncertainty and indecisiveness amongst dyslexic children, since such feelings might exacerbate their problems in reading.

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Chapter 5

Universal and language specific predictors of early word reading in a foreign language. An analysis of the skills that underlie reading acquisition in three different orthographies

Based on: Zeguers, M.H.T., Boer, M., van den, Snellings, P. & Jong, P.F., de. (in revision). Universal and language specific predictors of early word reading in a foreign language. An analysis of the skills that underlie reading acquisition in three different orthographies.

Abstract

A central question in the field of foreign language acquisition is whether the processes involved in reading development in a foreign language are universal, or dependent on characteristics of the specific language involved. We investigated the impact of orthographic depth and writing system on word reading acquisition in a foreign orthography, by studying children who are proficient readers in the transparent alphabetic Dutch orthography and who learn to read simultaneously in the transparent alphabetic Spanish orthography, the opaque alphabetic French orthography and the non-alphabetic Chinese orthography. Results showed that the cognitive skills that were most important for learning to read differed between the three foreign languages. Word reading in Spanish appeared to depend most strongly on native language reading skills, whereas French word reading was mainly influenced by phonological awareness and verbal intelligence, and Chinese word reading by verbal as well as nonverbal intelligence. However, two skills, rapid naming and intelligence, were found to contribute to reading development in all three foreign languages. Findings thus suggest that although some of the cognitive skills that underlie foreign language word reading are universal, the influence of most cognitive skills is language specific. Both the orthographic depth and writing system of a language affect the processes involved in acquiring reading skills in this language as a foreign language learner.

Introduction

The ability to read and write in a foreign language is highly relevant in current international society, as it facilitates global communication and access to information. As a consequence, multilingualism has become the norm rather than the exception in many countries. An increasing number of people even master more than one foreign language. In fact, in addition to learning a new language that uses the same writing system as the native language, more and more people also learn a foreign language with a different writing system, such as speakers of English who learn Chinese or Arabic, or the other way around. It is therefore not surprising that scientific interest in foreign language acquisition increased sharply during the last decades (Sparks, Patton, Ganschow, Humbach & Javorsky, 2008). The vast majority of studies investigated the acquisition of a foreign alphabetic orthography, either by native speakers of another language with an alphabetic orthography (e.g. Lindsey, Manis & Bailey, 2003), or, to a lesser extent, by native speakers of a language with a nonalphabetic orthography (e.g. Pan, McBride-Chang, Shu, Liu, Zhang & Li, 2011). Studies that addressed the acquisition of a nonalphabetic orthography by native speakers of a language with an alphabetic orthography, however, are scarce, and none investigated the cognitive skills that underlie reading acquisition. Consequently, it is unclear which cognitive processes are involved when skilled readers of an alphabetic orthography learn to read in a foreign nonalphabetic orthography, and whether these processes are similar to or different from the processes that underlie learning a foreign alphabetic orthography. This in unfortunate since knowledge about the processes that underlie foreign language reading acquisition contributes to our understanding of foreign language learning, which may result in enhancement of foreign language education. Therefore, the current study investigates which cognitive skills are involved when readers of an alphabetic writing system (Dutch) develop word reading ability in a foreign language with a non-alphabetic writing system (Chinese) and also in two foreign languages with alphabetic writing systems (Spanish and French).

Perspectives on foreign language acquisition

Insight in reading acquisition in a foreign language has come from the work of Cummins (1979, 1984, 1991). According to his interdependence hypothesis, the level of competence that a reader achieves in a foreign language (L2) is a function of the competence that has been developed in the native language (L1). More specifically, L1 reading skills serve as the foundation for L2 reading acquisition, and L2 reading proficiency is thus dependent on reading proficiency in L1. A related hypothesis, the linguistic coding differences hypothesis (Sparks & Ganschow, 1991, 1993, 1995) also stresses the commonalities between L1 and L2, but focusses on the cognitive skills that underlie reading development. The linguistic coding differences hypothesis is based on the assumption that a common 'core' language component, consisting of phonological, orthographic, syntactic and semantic skills, underlies reading acquisition across languages (Kahn-Horwitz, Shimron & Sparks, 2005). Skills in L1 are assumed to provide the foundation for L2 learning, such that the skills that are essential for reading in L1 are also important for learning to read in L2.

A pressing question in the field of foreign language acquisition is whether the processes involved in reading development in a foreign language are universal, or dependent on the specific language involved. The linguistic coding differences hypothesis assumes that the same core language component underlies reading acquisition in all languages, suggesting that the influence of component skills on reading acquisition in a foreign language is universal across languages. However, a contrasting view is proposed by the script-dependent hypothesis (Geva & Siegel, 2000; Geva & Wade-Woolley, 1998). This hypothesis suggests that the cognitive skills that contribute to foreign language reading acquisition depend on characteristics of the specific language that is to be learned, such as the transparency with which the spoken language is represented in written form. Based on these perspectives on reading acquisition in a foreign language, we included both native language and cognitive skills in the current study and examined whether their effect is the same or different for the foreign languages studied.

Research that aims to disentangle universal and language specific contributions to reading development in a foreign language has generally adopted multiple group designs, either by comparing reading development in children who learn to read in their native language with children learning to read the same language as a second language (e.g. Chiappe & Siegel, 1999; Cisero & Royer, 1995; Comeau, Cormier, Grandmaison & Lacroix, 1999; Durgunoğlu, Nagy & Hancin-Bhatt, 1993; Geva, Yaghoub-Zadeh & Schuster, 2000; Geva & Yaghoub-Zadeh, 2006; Lindsey et al., 2003) or by contrasting bilinguals who learn the same L2 but differ in their L1 (Bialystok, Luk & Kwan, 2005). Results thus far suggest that both universal and language specific factors are involved in second language acquisition (Saiegh-Haddad & Geva, 2010). However, a disadvantage of these group comparisons is that participants may differ on more variables than their native language. The amount and type of reading instruction, L2 oral proficiency, support for reading development provided by parents, reading motivation and metacognitive awareness are just some of the factors on which group differences may exist, and it is practically impossible to control for all of them in a between-group design. Therefore, in the current study we investigated reading acquisition in different orthographies within the same group. That is, we aim to disentangle which underlying skills are universal and which are language specific predictors of reading acquisition in a foreign language, by studying Dutch children who simultaneously learn to read in Chinese, Spanish and French.

Linguistic characteristics of the foreign languages

Two important characteristics of languages that may influence the processes involved in reading development in a foreign language are the language's writing system and orthographic consistency. First, the writing system indicates the structure that is used to reflect spoken language in written form. With respect to the languages in the current study, Spanish and French, and the participants' native language Dutch, have alphabetic writing systems, whereas Chinese has a morphosyllabic writing system. Alphabetic writing systems consist of a restricted number of visual linear symbols (letters), which directly represent the sound structure of the language. Learning to read therefore requires mastering the letter-sound mappings, and the exceptions to these mappings. Morphosyllabic systems, in contrast, contain several thousand symbols (characters), which are visually complex and do not reflect the language's phonetic speech structure (DeFrancis, 1989; Mattingly, 1992). In the case of Chinese, most characters consist of at least two components (compound characters) and contain information that corresponds to both pronunciation at the syllable level and to meaning at the morpheme level. However, the clues about pronunciation are not always consistent and sometimes even misleading (Shu, Chen, Anderson, Wu & Xuan, 2003). Learning to read in Chinese occurs therefore in a more holistic, rather than phonetic analytic, manner (Hanley, Tzeng & Huang, 1999; Shu & Anderson, 1997).

The second characteristic of languages, orthographic consistency, refers to the consistency with which symbols correspond to speech sounds. Two of the foreign languages included in the current study, Spanish and French, have the same (alphabetic) writing system, but differ in the degree of orthographic consistency. That is, although the two alphabetic orthographies both contain letters that represent speech sounds, the complexity of the letter-speech sound correspondences is rather different. Spanish, on the one hand, is orthographically shallow, which indicates that a given letter is generally pronounced identically across words. French, on the other hand, is orthographically deeper, with less consistent correspondences between letters and speech sounds. The native language of the participants in this study, Dutch, also has an alphabetic orthography. Dutch is considered to be orthographically shallow, although somewhat less shallow than Spanish (Seymour, Aro & Erskine, 2003). By investigating the simultaneous acquisition of Spanish, French and Chinese within the same participants, the current study allows to investigate to what degree different native language and cognitive skills are universal predictors of foreign language acquisition, or whether their influence depends on the language's writing system and orthographic consistency.

Reading acquisition in native speakers of languages with alphabetic orthographies

Insight in the cognitive skills that underlie reading acquisition comes from research in children who learn to read in their native language. This research mainly focused on reading acquisition in alphabetic orthographies. Across orthographies, two cognitive skills appear to be most influential in predicting reading development. These are phonological awareness, which denotes sensitivity to the sound structure of words, and rapid automatized naming (RAN), reflecting the ability to quickly name a set of highly familiar stimuli (e.g., Caravolas et al., 2012; de Jong & van der Leij, 1999; Moll et al., 2014; Muter, Hulme, Snowling & Stevenson, 2004; Wolf & Bowers, 1999; Ziegler et al., 2010). Specifically, alphanumeric RAN (rapid naming of letters and digits) appears more predictive than non-alphanumeric RAN (objects and colors; Bowey, McGuigan & Ruschena, 2005; Georgiou, Parrila & Liao, 2008). Other cognitive skills that have been found to contribute are vocabulary (Nation & Snowling, 2004; Ouelette, 2006; Ziegler et al., 2010), letter-sound knowledge (Caravolas et al., 2012; Foulin, 2005), orthographic processing skills (Cunningham, Perry & Stanovich, 2001;

Leslie & Thimke, 1986) and verbal memory (Landerl & Wimmer, 2008; Siegel, 1994; Swanson, Zheng & Jerman, 2009).

Recently, some cross-linguistic studies examined the impact of orthographic depth on the strength of various cognitive predictors. However, results are somewhat mixed. Some studies report equal impact of phonological awareness across orthographies (Caravolas, Lervåg, Defior, Málková & Hulme. 2013; Patel, Snowling & de Jong, 2004), whereas others suggest that phonological awareness is more important in deep than shallow orthographies (Georgiou, Parrila & Papadopoulos, 2008; Mann & Wimmer, 2002; Moll et al., 2014). Similarly, RAN has been found to be of equal influence in different orthographies by some researchers (Caravolas et al., 2013; Patel et al., 2004; Vaessen et al., 2010; Ziegler et al., 2010), whereas others report RAN to be more important in shallow than deep orthographies (Georgiou et al., 2008; Mann & Wimmer, 2002).

Reading acquisition in native speakers of Chinese

Since Chinese characters do not map onto phonemes as letters in alphabetic languages do, it has been questioned whether phonological awareness is involved in Chinese reading acquisition. Most research in Chinese children who learn to read in their native language has shown that, similar to alphabetic orthographies, phonological awareness is an important skill underlying reading acquisition (Ho & Bryant, 1997; McBride-Chang & Ho, 2000; McBride-Chang & Kail, 2002; Perfetti & Zhang, 1991; Zhou, Duff & Hulme, 2015, but see Huang & Hanley, 1997; Yeung et al., 2011). Rapid naming has also been identified as an important predictor of Chinese reading ability (Liao, Georgiou & Parrila, 2008; McBride-Chang & Kail, 2002; McBride-Chang & Ho, 2005; Pan et al., 2011; Yeung et al., 2011), and verbal memory has been found to contribute as well (Ho, 1997; Hu & Catts, 1998; So & Siegel, 1997). In fact, the effects of various cognitive predictors on reading development appeared rather similar in Chinese and English beginning readers (McBride-Chang & Kail, 2002).

Despite these similarities, a recent meta-analysis on the influence of phonological awareness and RAN on Chinese word reading (Song, Georgiou, Su, & Hua, 2016) compared its outcomes with meta-analyses in alphabetic orthographies (Araújo, Reis, Petersson & Faísca, 2015; Melby-Lervåg, Lyster & Hulme, 2012; Scarborough, 1998; Swanson, Trainin, Necoechea & Hammill, 2003) and suggested that the influence of phonological awareness may be somewhat smaller in Chinese than in alphabetic orthographies whereas the influence of RAN is of similar strength across writing systems. In addition, although the relation with Chinese reading is generally found to be larger for graphological RAN (characters and digits) than for non-graphological RAN (objects and colors), thereby mimicking effects in alphabetic orthographies (Song et al., 2016), some studies show that object naming correlates equally well with Chinese word reading as digit or character naming (e.g., Ding, Richman, Yang & Guo, 2010; McBride-Chang, Shu, Zhou, Wat & Wagner, 2003).

Interestingly, two skills that are of limited importance for alphabetic word reading, have been identified as predictors of reading acquisition in Chinese. These are morphological awareness (McBride-Chang et al., 2003; Yeung et al., 2011) and visual skills such as visual discrimination, visual form recognition, visual closure, visual-spatial reasoning and picture copying (Ho & Bryant, 1999; Huang & Hanley, 1995; McBride-Chang, Chow, Zhong, Burgess & Hayward, 2005; Siok, Spinks, Jin & Tan, 2009; Tan, Spinks, Eden, Perfetti & Siok, 2005; but see Ho, 1997; Hu & Catts, 1998; McBride-Chang & Kail, 2002). Visual skills seem to be especially important during the initial stages of reading development (Ho & Bryant, 1997; Siok & Fletcher, 2001). In sum, although findings are not yet unequivocal, it seems that some predictors of reading acquisition are universal, whereas other predictors may be language specific, and both orthographic depth and writing system appear to influence the strength of certain predictors on children's reading acquisition in their native language.

Reading acquisition in a foreign orthography

Research on the acquisition of reading skills in a foreign orthography has predominantly focused on native speakers of languages with alphabetic orthographies who learn to read in other alphabetic orthographies. A central aim in this research is to identify whether the cognitive skills that are essential for reading in L1 are also important for L2 reading acquisition. Most studies focused on phonological awareness and RAN, and showed that these skills, measured in both L1 and L2, predict reading development in L2 (Chiappe & Siegel, 1999; Cisero & Royer, 1995; Comeau et al., 1999; Durgunoğlu et al., 1993; Geva & Yaghoub-Zadeh, 2006; Geva et al., 2000; Lindsey et al., 2003; Morfidi, van der Leij, de Jong, Scheltinga & Bekebrede, 2007). Research on other cognitive skills has not yet converged to unambiguous results. Skills that have been shown to transfer from L1 to L2 are verbal memory (Comeau et al., 1999; Geva & Siegel, 2000, but see Lindsey et al., 2003); orthographic knowledge (Sun-Alperin & Wang, 2011), oral language proficiency (Lindsey et al., 2003, Manis, Lindsey & Bailey, 2004; but see Durgunoğlu et al., 1993) and letter knowledge (Lindsey et al., 2003, Durgunoğlu et al., 1993). In addition, word reading skills in L1 are generally directly related to word reading in L2, which indicates that the more proficient readers are in their native alphabetic language, the better they tend to perform in reading a foreign alphabetic language as well (Bialystok et al., 2005; Geva & Siegel, 2000; Gholamain & Geva, 1999; Gottardo, 2002; Lindsey et al., 2003; Morfidi et al., 2007; Swanson, Sáez, Gerber & Leafstedt, 2004; Wade-Woolley & Geva, 2000).

The skills that underlie learning to read in a new writing system have received relatively little scientific interest, and are to our knowledge not yet studied in skilled readers of alphabetic orthographies learning to read in a nonalphabetic orthography. The few studies that focused on cross-writing system literacy acquisition have mainly investigated native speakers of Chinese who learn to read in English. It has been suggested that transfer of literacy related cognitive skills is limited to bilinguals whose L1 and L2 have the same writing system (Bialystok et al., 2005). However, several studies indicate that, similar to transfer between two alphabetic orthographies, phonological awareness in Chinese predicts reading development in English (Chow, McBride-Chang & Burgess, 2005; Gottardo, Yan, Siegel & Wade-Woolley, 2001; Pan et al., 2011; Wang, Perfetti, & Liu, 2005; see Wang, Park & Lee, 2006 for similar findings in Korean-English bilinguals, but see Huang & Hanley 1997). There is also evidence for cross-writing system transfer of RAN (Geva et al., 2000; Gholamain & Geva, 1999; Pan et al., 2011, but see Gottardo et al., 2001). Research on the cross-writing system transfer of other cognitive skills is scarce. Some studies report influences of Chinese orthographic processing skills on English word reading (Leong, Hau, Cheng & Tan, 2005; Tong & McBride-Chang, 2010), whereas others do not find transfer of orthographic skills (Gottardo et al., 2001; Wang, Park & Lee, 2006; Wang et al., 2005).

Similarly, although in some studies a relation is found between Chinese and English word reading (Wang, Cheng & Chen, 2006, and Wang, Park & Lee, 2006 report a relation between word reading in Korean and English), word reading skills in Chinese are generally not found to be predictive of word reading in English (Gottardo et al., 2001; Bialystok, Luk & Kwan, 2005; Bialystok, McBride-Chang & Luk, 2005; Wang et al., 2005). In sum, there is still quite some uncertainty about the degree to which literacy skills and related cognitive skills transfer between L1 and L2, and whether this transfer is influenced by the orthographic depth and specifically the writing system of the languages involved.

The current study

The current study aims to clarify to what extent native language skills and cognitive skills involved in reading acquisition in a foreign language are universal or depend on the writing system and orthographic transparency of the language concerned. We addressed this issue by investigating 12-13 year old children who are proficient readers in the transparent alphabetic Dutch orthography and who learn to read simultaneously in the transparent alphabetic Spanish orthography, the opaque alphabetic French orthography and the morphosyllabic Chinese orthography. Development in all three foreign languages was assessed during the first 10 months that these languages were acquired, which was the period of the first year of secondary education. Reading acquisition was measured at the word level, since we assumed this would best capture progress during the first stages of language acquisition. A novel aspect of this study is the focus on reading acquisition in a nonalphabetic L2, by children with an alphabetic L1. In addition, the study is the first to adopt a design in which multiple foreign languages, which differ in writing system and orthographic depth, are simultaneously acquired by the same participants. The main research question in the current study is which language and cognitive skills are predictive of reading acquisition across foreign languages, and which are dependent on the orthographic depth or writing system of the language involved. In order to answer this question, we selected reading skills in the participants' native language Dutch, as well as cognitive skills that the literature reviewed above suggested to be involved in reading development in either a) L1 readers of alphabetic orthographies, b) L1 readers of Chinese, c) L1 readers of one alphabetic orthography who learn to read in another alphabetic orthography, and d) Chinese readers who learn to read in an alphabetic orthography. In addition, we included skills that are expected to relate to learning in general.

Based on the literature reviewed above, it could be expected that reading development in the alphabetic orthographies depends most strongly on phonological awareness and RAN, whereas visual skills are especially important for reading in Chinese. Amongst the alphabetic orthographies, the relative influence of phonological awareness and RAN may differ, due to differences in orthographic depth. Phonological awareness may be more important in the deep French orthography, whereas RAN may be of larger influence in the transparent Spanish orthography. By including reading fluency in Dutch we examined whether the influence of these cognitive skills on word reading in a foreign language is specific, or rather due to their influence on reading acquisition in the participants' native language. Besides these specific hypotheses, it should also be acknowledged that foreign language learning is an academic task that entails mastering new knowledge and skills. Therefore, like academic performance in general, word reading in the three foreign languages may depend on general learning abilities, in particular intelligence.

Method

Participants

One hundred and eighty-five children (83 boys) participated in this study. Their mean age was 12 years 4 months (*SD* = 5.19 months) at the start of the study. Most participants (97.8%) spoke Dutch at home, although many children (40.5%) also spoke another language with their families. All children attended the first year of secondary education at an inner-city school in the Netherlands. In the Netherlands, secondary education is provided in different levels. Participants were all in the highest two levels, meaning that they were among the average to above average students (top 50%). The children were provided with Dutch-English bilingual education. In addition, they received classes in three different foreign languages: Spanish, French and Chinese. For each of these languages students had two 50-minute classes per week.

Measures

Foreign language skills

We administered a word translation task at the beginning of the study, to distinguish between children who just started to learn Spanish, French and Chinese, and children who already mastered one of these languages. These tasks were designed for the purpose of the current study, and were based on the curriculum of the students. Stimuli for the tasks were selected from the glossary of the first year curriculum. Therefore, the tasks measured whether students already knew the words they would be studying in class, before classes started. Students were presented with a list of words of increasing difficulty. They were asked to read the words and write down as many translations to Dutch as possible within 3 minutes. The Spanish and French versions consisted of 96 words each. The Chinese version consisted of 60 characters. The scores were the number of words that were translated correctly to Dutch.

Foreign language word reading

For each of the three languages studied (Spanish, French, Chinese), children were administered a word reading task to measure reading skill. Similar to the translation task, these tasks were designed for the purpose of the current study, and were based on the curriculum of the students. A word was always presented either in the reading task or in the translation task, never in both. Children were presented with a list of words of increasing difficulty that they were asked to read aloud as quickly and accurately as possible for 1 minute. The Spanish and French versions consisted of 96 words each. The Chinese version consisted of 60 characters. The scores were the number of words read correctly.

Dutch reading fluency

Reading fluency in Dutch was measured with two standardized reading tests that are regularly used in Dutch schools as a measure of reading achievement: the One Minute Test (*Eén Minuut Test*; Brus & Voeten, 1995) for word reading and the Klepel (van den Bos, Lutje Spelberg, Scheepstra & de Vries, 1994) for pseudoword reading.

Word reading. Children were asked to read aloud a list of 116 words of increasing difficulty as quickly and accurately as possible for 1 minute. The score consisted of the number of words read correctly.

Pseudoword reading. Children were asked to read aloud a list of 116 pseudowords of increasing difficulty as quickly and accurately as possible for 2 minutes. The score consisted of the number of pseudowords read correctly.

Cognitive skills

Seven cognitive skills were included in the study: verbal intelligence, nonverbal intelligence, phonological awareness, alphanumeric RAN, nonalphanumeric RAN, visual processing speed, and verbal memory. Two or three measures were included to assess each of these skills, amounting to a total of 16 tasks. These tasks were all administered in Dutch.

Verbal intelligence

Verbal intelligence was examined with subtests of three different tests for intelligence or academic learning potential: the verbal scale of the Dutch intelligence test of educational level (*Nederlandse Intelligentietest voor Onderwijsniveau* (NIO); van Dijk & Tellegen, 2004), the subtest Dutch vocabulary from the Cito Test 0 (van Til & van Boxtel, 2015), and the subtest verbal reasoning from the General Aptitude Test Battery (GATB; van der Flier & Boomsma-Suerink, 1990).

Verbal IQ. The NIO verbal scale includes three subtests: synonyms, analogies, and categories. For each of these subtests children are asked to answer multiple choice questions as quickly and accurately as possible for five minutes. Based on the performance on these subtests a standardized score is calculated with a mean of 100 and a standard deviation of 15.

Dutch vocabulary. Cito Test 0 comprised a total of six tasks, with a maximum duration of 50 minutes per task. The subtest Dutch vocabulary consisted of 50 multiple choice items.

The number of items correct is converted to a scaled score. This scaled score can be used to compare scores across tests and schoolyears, although this was not done in the current study.
Verbal reasoning. Children were presented with four words. They were asked to choose two words that were either synonyms or antonyms. The test consisted of 50 items. Children were asked to complete as many items as possible within four minutes. The score consisted of the number of items correct.

Nonverbal intelligence

Nonverbal intelligence was examined with subtests from the same tests as for verbal intelligence: the symbolic scale from the NIO (van Dijk & Tellegen, 2004), the subtest math from the Cito Test 0 (van Til & van Boxtel, 2015), and the subtest spatial reasoning from the GATB (van der Flier & Boomsma-Suerink, 1990).
Nonverbal IQ. The symbolic scale of the NIO consisted of three subtests: numbers, math, and figures. The duration of each of these subtests was 10 minutes (15 minutes for math). Based on the performance on these subtests a standardized score is calculated with a mean of 100 and a standard deviation of 15.
Math abilities. The subtest mathematics consisted of 68 multiple choice items. The number of items correct is converted to a scaled score.
Spatial reasoning. Children were presented with a target picture of a two-dimensional figure that included folding lines. They were asked to choose from among four options the three-dimensional figure that could be created by folding the target figure. The task consisted of 40 items. Children were asked to answer as many items as possible within four minutes. The score consisted of the number of items correct.

Phonological awareness

To assess phonological awareness we used a computerized version of a phoneme deletion task (de Jong & van der Leij, 2003), programmed in E-prime (Schneider, Eschman, & Zuccolotto, 2002). The task consisted of two parts and separate scores were calculated for each part.
Phoneme deletion 1 phoneme. Children heard a bisyllabic nonword (e.g., '*memslos*'). Next, they heard the nonword again, but were also asked to delete one phoneme (e.g., 'what is *memslos* without 'l'?). The task consisted of 9 items. When the participant had answered the experimenter pressed the space bar to register reaction time and indicated whether the answer was correct or incorrect. The score was calculated by converting the median reaction time to the number of items answered per minute and multiplying that score by the proportion of items correct.
Phoneme deletion 2 phonemes. Following the same procedure, children were presented with 9 bisyllabic nonwords in which the phoneme to be deleted occurred twice (e.g., 'what is *gepgral* without 'g').

Rapid Automatized Naming (RAN)

RAN performance was measured with four subtests of the Test of Continuous Naming and Word Reading (*Continue benoemen en woorden lezen*; van den Bos & lutje Spelberg, 2007). A distinction was made between alphanumeric and nonalphanumeric RAN.

Alphanumeric RAN. Alphanumeric RAN was measured with digit and letter naming. Five digits (2, 4, 5, 8, 9) were presented 10 times each in a semi-random order in 5 columns of 10 items. Children were asked to name aloud all 50 digits as quickly and accurately as possible. The experimenter recorded the time needed to name all digits, which was converted to the number of items named per second. Naming of letters (a, d, o, p, s) was administered in the same way.

Nonalphanumeric RAN. Nonalphanumeric RAN was measured with color (black, blue, green, red, yellow) and picture (bike, chair, duck, scissors, tree) naming following the same procedure as for alphanumeric RAN.

Visual processing speed

Visual processing speed was assessed with coding and symbol search, two subtests of the Wechsler Intelligence Scale for Children (WISC-III-NL; Kort et al., 2005).

Coding. Children were presented with a key consisting of the digits 1 through 9, each paired with a unique symbol. Underneath the key children encountered a sequence of 119 randomly ordered digits. They were asked to write down the corresponding symbol for as many digits as possible, within two minutes. They were asked to work from left-to-right, without skipping digits. The score consisted of the number of symbols copied correctly.

Symbol search. Children saw a string with two symbols on the left and five symbols on the right. They were asked to indicate by crossing either 'yes' or 'no' whether one of the two symbols on the left also appeared in the row of symbols on the right. They were presented with a total of 45 items and were asked to complete as many items as possible within 2 minutes. The score consisted of the number of correct judgments.

Verbal memory

We used the digit span task from the WISC-III-NL (Kort et al., 2005) to assess verbal memory. This task consists of two parts for which separate scores were calculated.

Digit span forward. The experimenter read aloud a digit sequence and the child was asked to repeat the digits in the correct order. The sequences increased in length from two to nine digits with two sequences of each length. When both sequences of the same length were repeated incorrectly the task was discontinued. The score consisted of the number of sequences repeated correctly.

Digit span backward. For digit span backward the experimenter again read aloud digit sequences. This time, however, children were asked to repeat these sequences in reversed order. The sequences increased in length from two to eight digits, with two sequences of each length. The discontinuation rule was again applied. The score consisted of the number of sequences repeated correctly.

Procedure

The children's progress in foreign language word reading was followed for one year from September 2014 until June 2015. All the tasks for literacy as well as cognitive skills were administered in September 2014 (T1) by the first and second author and well-trained assistants. At that time children took part in one classroom session and one individual session of 45 minutes each. The tasks verbal reasoning, coding, spatial reasoning, and symbol search were administered in fixed order during the classroom session, as well as a questionnaire for background variables. The other tasks were administered in the individual session, also in a fixed order: word reading, pseudoword reading, digit span (forward, backward), RAN (colours, digits, objects, letters), French word reading, phoneme deleatio (one phoneme, two phonemes), Spanish word reading. Children participated in a second and third session in February 2015 (T2) and June 2015 (T3) respectively. During these sessions only the foreign language word reading tasks were administered for a second and third time. The Chinese tasks were administered by the teachers of the children. The NIO (van Dijk & Tellegen, 2004) and Cito Test 0 (van Til & van Boxtel, 2015) were administered by the school, before the start of this study. The NIO was administered group-wise three months before the start of the schoolyear by an external psychologist, as part of the school's registration procedure. The Cito Test 0 was administered group-wise on the computer during the first month of the schoolyear, as the first of a sequence of measurements aimed at following students' progress in Dutch, English and mathematics. The scores on these tasks were provided to the researchers by the school principal.

Analyses

The main research question of the current study concerned similarities and differences in the relations of native language and cognitive skills with the acquisition of word reading skills in three foreign languages, that is Spanish, French, and Chinese. Multiple tasks were used to measure each skill included in the study. Therefore, a structural equation model with latent variables was fitted to the data. First a factor model was fitted in which all indicators loaded on their respective latent variable and all latent variables were correlated. After model fit was deemed acceptable, the correlations between latent variables were examined to determine how native language and cognitive skills related to reading acquisition in Spanish, French and Chinese. Next, we specified a regression model in which all cognitive skills had direct effects on reading acquisition in Spanish, French, and Chinese. In this model, a significant regression coefficient indicated that the cognitive skill uniquely explained variance in reading acquisition when the relations between predictors were controlled for. Finally, we specified a regression model in which all cognitive skills had an effect on word reading in the foreign languages, but also on reading skills in the native language, which in turn had an effect on word reading in the foreign languages. This model aimed to examine whether the included cognitive skills had a specific effect on word reading in the foreign languages, or whether a relation between the cognitive skills and word reading in the foreign languages is simply due to the relation of these cognitive skills with reading skills in the native language.

The models were fitted with Mplus Version 7.11 (Muthén & Muthén, 2012), using full information maximum likelihood estimation. Model fit was evaluated using the chi-square statistic of overall goodness of fit, the comparative fit index (CFI), the standardized root mean square residual (SRMR) and the root mean square error of approximation (RMSEA). A chi-square *p*-value larger than .05 indicates exact fit (Hayduck, 1996). A CFI larger than .95 in combination with a SRMR below .08 indicates good approximate fit (Hu & Bentler, 1999). Values of the RMSEA below .05 indicate close fit, below .08 satisfactory fit, and values over .10 indicate poor fit (Browne & Cudeck, 1993).

Results

Data cleaning

Before running analyses, data were inspected for missing values and outliers. In the current study we examined foreign language reading acquisition in the very early stages. In general, students had no or very little experience with Spanish, French and Chinese at the start of the study. Therefore, for each of the foreign languages studied, children were excluded from analyses if they indicated to speak the language at home, or if their performance on the translation task was more than three standard deviations above the group mean. For Spanish and French, data of four children were coded as missing. In addition, data of one child with dyslexia were excluded for French, because he did not attend the French classes. For Chinese, data of five children were coded as missing.

Across tasks some scores were missing because children were absent during one of the sessions, did not perform a specific task correctly or because they missed tests that were administered before the start of the study. In addition, scores that were more than three standard deviations above or below the group mean were considered outliers and coded as missing. As a result of these missing data and outliers the number of observations is different for each task. The exact *N* for each task is presented with the descriptive statistics.

Word reading acquisition

Descriptive statistics for the foreign language word reading tasks are presented in Table 1. As expected, the scores on these tasks increased throughout the year. At the start of the study, children knew hardly any words, especially in Chinese. Most children were able to read a few words in French or Spanish, mostly because some letter-sound correspondences and words are the same across alphabetic languages, but also because they had visited France or Spain during the holidays. The largest growth in the children's reading skills appears to occur between T1 and T2. Their skills continued to improve between T2 and T3, although at a slower rate.

Table 1
Descriptive statistics of reading tasks

	N	*M (SD)*	Range
Spanish word reading T1	179	22.66 (8.57)	4 – 52
Spanish word reading T2	179	36.56 (11.04)	9 – 71
Spanish word reading T3	179	46.15 (12.17)	14 – 82
French word reading T1	179	19.99 (9.31)	3 – 53
French word reading T2	179	34.07 (12.07)	8 – 66
French word reading T3	178	39.30 (14.08)	5 – 78
Chinese word reading T1	180	0.08 (0.68)	0 – 7
Chinese word reading T2	178	13.80 (8.38)	0 – 33
Chinese word reading T3	177	15.60 (9.65)	1 – 45

At T1 children had not yet received classes for the languages studied. The literacy tasks were merely administered at T1 to determine if some children were already familiar with any of the languages. Their scores at T2 and T3 were used to determine children's reading acquisition. The correlations among the reading tasks at T2 and T3 are presented in Table 2. All correlations were significant (*p*'s < .01). As expected, the strongest correlations were found within each language between T2 and T3 performance. Across languages, reading performance was found to correlate moderately. Strong correlations were found between word reading in Spanish and French. Correlations of reading performance in French and Spanish with reading in Chinese were less strong.

Table 2
Correlations among the reading tasks

	1	2	3	4	5	6
1. Spanish word reading T2	-					
2. Spanish word reading T3	.848	-				
3. French word reading T2	.741	.679	-			
4. French word reading T3	.569	.646	.727	-		
5. Chinese word reading T2	.459	.545	.421	.439	-	
6. Chinese word reading T3	.458	.523	.419	.395	.864	-

Note. All correlations are significant at $p < .01$.

Native language and cognitive skills

Descriptive statistics for the predictors of foreign language word reading, i.e. the native language and cognitive skills, are presented in Table 3. Scores were normally distributed for all tasks. The correlations among the native language and cognitive skills are provided as supplementary material (Table S6). As expected, the strongest correlations were found between tasks that were used to measure the same skill. For verbal memory, the correlation between the two tasks measuring this skill was low. Therefore, we decided not to construct a latent variable verbal memory based on these two tasks. We used a composite score instead.

The correlations of the predictors with foreign language reading performance are shown in Table 4. In all three foreign languages, the correlations of native language and cognitive skills with reading performance was very similar at T2 and T3. Moreover, correlations between word reading on T2 and T3 was high in all three languages, Therefore, it seemed best to model word reading performance on T2 and T3 as two indicators of one latent 'reading performance' variable for each of the three foreign languages. An additional benefit of taking word reading at T2 and T3 as indicators of one latent construct is that the latent construct reading represents a more reliable estimate of individual differences in word reading in the foreign languages.

Table 3
Descriptive statistics of native language and cognitive skills

	N	*M (SD)*	Range
Dutch word reading	184	87.08 (11.78)	52 – 116
Dutch pseudoword reading	182	74.46 (15.11)	38 – 116
Verbal IQ	164	109.26 (11.24)	84 – 138
Dutch vocabulary	182	241.85 (25.53)	167 – 315
Verbal reasoning	180	13.77 (5.30)	0 – 28
Nonverbal IQ	164	111.50 (10.70)	87 – 140
Math abilities	182	240.43 (14.60)	197 – 274
Spatial reasoning	180	18.12 (4.57)	6 – 28
Deletion 1 phoneme	183	16.63 (6.66)	1.05 – 33.40
Deletion 2 phonemes	182	8.98 (4.54)	0.00 – 23.01
RAN letters	181	2.54 (0.37)	1.56 – 3.57
RAN digits	183	2.35 (0.44)	1.22 – 3.57
RAN colors	182	1.37 (0.25)	0.70 – 2.08
RAN pictures	184	1.28 (.20)	0.81 – 1.85
Coding	179	52.41 (10.40)	26 – 79
Symbol search	180	32.46 (5.05)	18 – 43
Digit span forward	183	8.28 (1.45)	5 – 12
Digit span backward	182	5.54 (1.61)	2 – 10

Table 4
Correlations of native language and cognitive skills with reading performance

	Spanish		French		Chinese	
	T2	T3	T2	T3	T2	T3
1. Dutch word reading	.506**	.496**	.344**	.311**	.181*	.173*
2. Dutch pseudoword reading	.514**	.497**	.318**	.222**	.125	.141
3. Verbal IQ	.322**	.221**	.278**	.357**	.335**	.293**
4. Dutch vocabulary	.212**	.248**	.225**	.324**	.368**	.350**
5. Verbal reasoning	.206**	.175*	.230**	.336**	.354**	.319**
6. Nonverbal IQ	.125	.150	.111	.137	.449**	.441**
7. Math abilities	.120	.158*	.136	.097	.353**	.397**
8. Spatial reasoning	-.019	.012	.049	.061	.171*	.185*
9. Deletion 1 phoneme	.355**	.325**	.250**	.227**	.088	.108
10. Deletion 2 phonemes	.372**	.348**	.326**	.299**	.075	.068
11. RAN letters	.234**	.295**	.108	.105	.069	.021
12. RAN digits	.229**	.235**	.047	-.016	.006	-.073
13. RAN colors	.272**	.322**	.139	.083	.211**	.194*
14. RAN pictures	.228**	.275**	.056	.103	.172*	.155*
15. Coding	.133	.127	.085	.042	.200**	.193*
16. Symbol search	.058	.019	.024	.030	.126	.130
17. Digit span forward	.144	.185*	.036	.047	.075	.077
18. Digit span backward	.194*	.204**	.081	.110	.187*	.224**

Note. * $p < .05$. ** $p < .01$.

The patterns in the correlations with the reading tasks were different for the various native language and cognitive skills. Native language reading skills correlated moderately with Spanish, weakly with French, and hardly with Chinese. Tasks that were used to measure verbal intelligence (verbal IQ, Dutch vocabulary, verbal reasoning) correlated weakly to moderately with all the reading tasks. The tasks reflecting nonverbal intelligence (nonverbal IQ, math abilities, spatial reasoning) appeared to correlate mainly with Chinese. Phonological awareness correlated only with reading acquisition in the alphabetic languages Spanish and French. Alphanumeric RAN correlated only with reading in Spanish. For nonalphanumeric RAN, weak correlations were found with the Spanish and the Chinese reading tasks. Weak correlations were found between visual processing speed (coding and symbol search) and reading acquisition in Chinese. Finally, verbal memory correlated weakly with reading acquisition in Spanish and Chinese, although this was mainly true for digit span backward.

Correlates of word reading acquisition in Spanish, French, and Chinese

To examine the relations among the foreign language reading tasks and the predictor tasks, a factor model was fitted to the data, as shown in Figure 1. Because the two indicators of verbal memory correlated weakly, a single indicator latent factor was included in the model, based on the sum of the two indicators. To model this single indicator latent variable, the residual variance of the indicator was fixed to the variance of the indicator multiplied by 1 minus the reliability of the task (which is .63; Kort et al., 2005). This model provided a good approximate fit to the data, $\chi^2(176) = 249.73$, $p < .001$, RMSEA = .048 [.033-.061], CFI = .961, SRMR = .050. Therefore, no model modifications were necessary, including specific effects of predictor skills to reading performance at either T2 or T3. The standardized factor loadings and residual variances for all the indicators are presented in Figure 1. The standardized correlations among the latent native language and cognitive predictors are presented in the supplemental material (Table S7).

The main research question was whether the same native language and cognitive skills predict reading acquisition in Spanish, French and Chinese. First, we examined the correlations of the predictors with reading acquisition in the three languages. The standardized estimates of these correlations are presented in Table 5. Many significant positive correlations were found between the predictors and the reading tasks, but interestingly, the pattern of correlations differed across languages. First, native language reading skills correlated with reading performance in all three languages, although the correlation was highest with reading in Spanish, and only a weak correlation was found with reading in Chinese. Verbal and nonverbal intelligence were found to correlate significantly with reading acquisition in all three languages, although more strongly with Chinese than with either Spanish or French. Phonological awareness correlated with reading in Spanish and French. Alphanumeric RAN was found to correlate only with Spanish reading, whereas nonalphanumeric RAN correlated significantly with reading in all three languages. Visual processing speed correlated only with reading in Chinese. And finally, verbal memory correlated significantly with reading in Spanish and Chinese.

Figure 1. Factor model as fitted to the data. Standardized factor loadings and residual variances are presented. Correlations among both predictors and reading acquisition factors were included in the model, but are not presented in the figure for clarity purposes.

Unique predictors of reading acquisition in Spanish, French, and Chinese

Because the cognitive skills are interrelated in many ways, we next examined the unique contribution of each cognitive skill in predicting word reading in Spanish, French, and Chinese. We therefore specified a regression model with effects of all cognitive predictors on reading acquisition in all three languages. In this simultaneous regression model, the effect of each predictor reflects the unique contribution of the predictor to reading acquisition, controlled for the other predictors in the model. In this first model we did not include native language reading skills. Therefore, the fit of the model was slightly different from the fit of the correlation model. This regression model also provided a good approximate fit to the data, $\chi^2(145) = 199.31$, $p = .002$, RMSEA = .045 [.028 - .060], CFI = .966, SRMR = .047. The standardized regression coefficients are presented in Table 5. Together, the cognitive skills predicted 46% of the variance in Spanish reading. This variance is mainly explained by verbal intelligence (.309, $p = .002$) and phonological awareness (.377, $p < .001$), which were the only significant unique predictors of reading in Spanish. The cognitive predictors explained 40% of the variance in French reading, also with verbal intelligence (.369, $p = .001$) and phonological awareness (.451, $p < .001$) as the significant predictors. Finally, the cognitive predictors explained 50% of the variance in reading acquisition in Chinese. The significant predictors were verbal intelligence (.339, $p < .001$) and nonverbal intelligence (.412, $p < .001$).

In the fitted models, alphanumeric and nonalphanumeric RAN were quite strongly correlated. This might lead to an underestimation of their unique effect on word reading in Spanish, French and Chinese. Therefore, two alternative models were examined in which either alphanumeric or nonalphanumeric RAN was included as a predictor, while the other was excluded from the model. Exclusion of alphanumeric RAN did not result in a significant effect of nonalphanumeric RAN on word reading in any of the three languages. Exclusion of nonalphanumeric RAN, however, resulted in a significant unique effect of alphanumeric RAN (.305, $p = .003$) on word reading in Spanish.

Finally, we examined whether the cognitive predictors had a specific effect on reading acquisition in each of the three languages, or whether this effect might be due to their effect on native language reading skills. We therefore specified another regression model in which the cognitive skills and also the native language skills were included. In this model, all cognitive skills had an effect on native language reading skills, as well as word reading in Spanish, French, and Chinese. Native language reading skills, in turn, were specified to have an effect on word reading in Spanish, French, and Chinese. As this model is an alternative model to the correlation model, the fit was the same. The standardized regression coefficients are presented in Table 5. Together, native language and cognitive skills explained 54% of the variance in Spanish reading. In this model, native language reading (.480, $p < .001$) was the only significant predictor of reading in Spanish, with no additional effects of the cognitive skills. The predictors accounted for 42% of the variance in French reading skills. As in the regression model without native language reading skills included, verbal intelligence (.290, $p =$

.017) and phonological awareness (.359, p = .007) were the significant predictors. The predictors explained 50% of the variance in reading in Chinese, still with verbal (.351, p = .002) and nonverbal intelligence (.397, p < .001) as the significant predictors.

Table 5
Standardized correlations and regression coefficients

Predictors	Spanish	French	Chinese
Correlations with native language and cognitive skills			
Native language reading	.647**	.443**	.194*
Verbal intelligence	.387**	.447**	.542**
Nonverbal intelligence	.216*	.221*	.574**
Phonological awareness	.552**	.495**	.138
Alphanumeric RAN	.316**	.097	.004
Nonalphanumeric RAN	.398**	.191*	.259**
Visual processing speed	.145	.078	.238**
Verbal memory	.308**	.153	.274**
Regression coefficients for cognitive skills only			
Verbal intelligence	.309**	.369**	.339**
Nonverbal intelligence	.118	.097	.412**
Phonological awareness	.377**	.451**	-.059
Alphanumeric RAN	.258	.106	-.053
Nonalphanumeric RAN	.048	-.067	.231
Visual processing speed	-.088	-.036	.014
Verbal memory	.050	-.071	.100
Regression coefficients for native language and cognitive skills			
Native language reading	.480**	.286	.013
Verbal intelligence	.194	.290*	.351**
Nonverbal intelligence	.112	.093	.397**
Phonological awareness	.221	.359**	-.059
Alphanumeric RAN	-.018	-.070	-.054
Nonalphanumeric RAN	.003	-.091	.210
Visual processing speed	-.053	-.008	.026
Verbal memory	.067	-.058	.103

Note. * p < .05. ** p < .01.

Discussion

The main aim of this study was to investigate whether native language and cognitive skills are universal predictors of word reading development in foreign languages, or whether their influence is dependent on the writing system or orthographic depth of the foreign language involved. To this end, we studied children who are proficient readers in the transparent alphabetic Dutch orthography and who learn to read simultaneously in the shallow alphabetic Spanish orthography, the deep alphabetic French orthography and the morphosyllabic Chinese orthography.

Correlational results showed that reading fluency in Spanish was related to all but one of the included predictor skills (ordered on strength of the correlations): native language reading skills, phonological awareness, nonalphanumeric RAN, verbal intelligence, alphanumeric

RAN, verbal memory and nonverbal intelligence. French reading fluency correlated with phonological awareness, verbal intelligence, native language reading skills, nonverbal intelligence and nonalphanumeric RAN. Finally, reading fluency in Chinese was related to nonverbal intelligence, verbal intelligence, verbal memory, nonalphanumeric RAN, visual processing speed and native language reading skills.

A regression model provided insight in the unique predictive strength of the cognitive skills on reading development in the three orthographies, when interrelations amongst these skills were controlled for. This model showed that the unique predictors of word reading development in Spanish and French were phonological awareness and verbal intelligence, whereas Chinese word reading was uniquely predicted by verbal and nonverbal intelligence. When nonalphanumeric RAN was excluded from the model, alphanumeric RAN was an additional unique predictor of word reading in Spanish.

A second regression model accounted for the possibility that cognitive skills influence reading development in the foreign languages, because of their effect on reading skills in the native language. This model identified to what extent the cognitive skills specifically predicted reading development in each of the three foreign orthographies, once their influence on native language skills, and in turn the effect of native language reading skills on word reading in a foreign language, was controlled for. Results indicated that the contribution of phonological awareness and verbal intelligence on Spanish reading development disappeared after controlling for native language reading skills. This suggests that phonological awareness and verbal intelligence contribute to Spanish word reading only because of their influence on reading skills in the native language. In contrast, word-reading acquisition in French and Chinese was not particularly influenced by native language reading skills. Phonological awareness and verbal intelligence were still the main and direct contributors to reading acquisition in French, and verbal and nonverbal intelligence still contributed uniquely and directly to reading acquisition in Chinese. Findings thus indicate that there are both similarities and remarkable differences across orthographies, with respect to the skills that underlie reading development.

It should be noted that the numerous interrelations amongst the predictor variables in the current study demand careful interpretation of the regression outcomes. That is, although the regression analyses identify only one or two skills as unique predictors of reading development in each of the three languages, this does not abolish the influence of other skills. Therefore, it seems important to evaluate the findings of the regression model in light of the correlational findings. However, since the correlations also reflect different patterns of predictor skills across the three foreign languages, this leaves the conclusion intact that although some of the cognitive skills that underlie foreign language reading acquisition are universal, the influence of cognitive skills is mainly language specific.

Insight in the influence of writing system on reading acquisition in a foreign language comes from comparisons between the predictors of reading development in the morphosyllabic Chinese writing system and the two alphabetic writing systems (Spanish and French). Results indicated that phonological awareness and native language reading skills are more important for learning to read in the two foreign alphabetic orthographies than for morphosyllabic Chinese, whereas the importance of nonverbal intelligence, and to a lesser extent visual processing speed, was larger in the morphosyllabic Chinese orthography than in the alphabetic orthographies. These findings thus support the assumption that reading acquisition in morphosyllabic orthographies depends less on phonological processing and more on visual processing than reading acquisition in alphabetic orthographies (Huang & Hanley, 1995; Siok & Fletcher, 2001). The current findings suggest that this pattern applies to foreign language acquisition as well. This result contrasts with research on Chinese reading development in native speakers of Chinese, where phonological skills have been shown to be involved (Ho & Bryant, 1997; McBride-Chang & Ho, 2000; McBride-Chang & Kail, 2002; Perfetti, & Zhang, 1991; Zhou et al., 2015), whereas the contribution of visual skills is disputed (Ho & Bryant, 1999; Huang & Hanley, 1995; McBride-Chang et al., 2005; Siok et al., 2009; Tan et al., 2005). This diverging pattern suggests that Chinese reading acquisition develops somewhat different in skilled readers of an alphabetic orthography who learn Chinese as a foreign language compared to Chinese readers who acquire reading skills in their native language. Readers of alphabetic orthographies are used to a writing system where visually simple letter symbols directly represent the phonemic structure of the language, and have to get acquainted with visually complex symbols for which the relation with speech sounds is either lacking or inconsistent. This may explain the relative importance of visual skills and limited influence of phonological processing skills in those who learn Chinese as a foreign language.

The finding that word reading in Chinese relates to different predictors than word reading in the alphabetic orthographies suggests that reading acquisition might call upon different learning strategies in foreign morphosyllabic writing systems relative to foreign alphabetic writing systems, at least for native speakers of languages with alphabetic orthographies. Learning to read in a foreign alphabetic writing system may occur through the formation of new letter-speech sound mappings. In contrast, the unavailable or unreliable letter-speech sound connections in Chinese render phonological strategies inefficient and may instead call for mappings between the visual and semantic form of the character. This would suggest that Chinese characters are initially acquired character by character. Although speculative at this point, this interpretation is supported by the finding that word reading in Spanish and French correlated strongly, whereas correlations with word reading in Chinese were much lower.

Comparisons between the shallow alphabetic Spanish orthography and deep alphabetic French orthography provided insight in the influence of orthographic depth on the predictors of reading development in a foreign language. The correlational results showed a substantial similarity between the predictors of reading acquisition in both alphabetic orthographies. The difference mainly resided in the influences of RAN and verbal memory. Both seem more important for reading development in shallow than deep orthographies, which has also been reported for reading development in L1 readers (Ziegler et al., 2010). Findings were still highly similar when unique contributions of the cognitive skills were examined, as in both languages phonological awareness and verbal reasoning were the main unique predictors. However, marked differences were found between the two alphabetic orthographies when their influence on native language reading skills was taken into consideration in the predictive ability of the cognitive skills. Whereas Spanish reading development was now only uniquely influenced by reading skills in the native language, reading development in French was still uniquely predicted by phonological awareness and verbal intelligence. This indicates that, whereas phonological awareness and verbal intelligence are specifically involved in French reading acquisition, they contribute to Spanish reading acquisition because of their impact on native language reading skills. That is, phonological awareness and verbal reasoning are related to the development of reading proficiency in the native language Dutch, but it is Dutch reading skill that is most important for the subsequent acquisition of Spanish reading skills.

The current findings bear upon each of the three perspectives on foreign language acquisition that were reviewed in the *Introduction*. In accordance with the interdependence hypothesis (Cummins, 1979; 1984; 1991), Spanish reading development depends mainly on literacy skills in Dutch. That is, reading skills in Spanish seem to build upon the reading skills that participants already acquired in their native language. Dutch reading skills also appeared to influence reading development in French and, to a lesser extent, in Chinese. However, in French and Chinese, the contribution of Dutch reading skills was inferior to that of other skills. This indicates that when native speakers of a language with a transparent alphabetic orthography learn another transparent alphabetic language, they can use their native language reading skills as a foundation for the development of reading skills in the foreign language. However, when the foreign language that is acquired contains more complex letter-speech sound mappings (French), or a different writing system (Chinese), additional cognitive skills are required to develop reading fluency.

Whereas the interdependence hypothesis focuses on the influence of L1 reading skills on L2 reading skills, the linguistic coding differences hypothesis and script dependent hypothesis focus on the contribution of underlying cognitive skills in L1 on L2 reading development. In line with the Linguistic coding differences hypothesis (Sparks & Ganschow, 1991, 1993, 1995) verbal and nonverbal intelligence as well as nonalphanumeric RAN correlated with reading development in all three foreign languages. Since RAN has been shown to relate to reading fluency in many languages (e.g., Ziegler et al., 2010), this skill qualifies as a candidate for a common language component, underlying literacy acquisition universally. However, in our study we specifically found nonalphanumeric RAN to relate to reading development in all languages, whereas it is generally found that alphanumeric RAN more strongly relates to reading development (e.g., Georgiou et al., 2008). Nevertheless, when interrelations with other cognitive skills were taken into account, nonalphanumeric RAN did not have a unique effect on word reading in any of the languages, indicating that its effect is neither strong nor specific. Furthermore, the current findings suggest that also more general reasoning skills, both verbal and nonverbal intelligence function as universal predictors of reading development in a foreign language. Verbal intelligence, in particular, was found to uniquely predict word-reading acquisition across languages. These two issues will be readdressed below.

Importantly, the current findings indicate that a common language component cannot fully explain reading development in all foreign languages. Besides the similarities related to verbal and nonverbal intelligence and nonalphanumeric RAN, there were striking differences in the cognitive skills that underlie reading development in the three foreign languages studied. This pattern suggests that, in line with the script-dependent hypothesis (Geva & Siegel, 2000; Geva & Wade-Woolley, 1998), the cognitive skills that contribute most strongly to reading acquisition depend on characteristics of the specific foreign language involved. Thus, reading acquisition in Spanish depends most strongly on native language reading skills and cognitive skills contributed only because of their influence on native language reading skills. In contrast, French reading acquisition is mainly influenced by phonological awareness and verbal intelligence, and Chinese reading acquisition by verbal as well as nonverbal intelligence. Our findings thus suggest that although some of the cognitive skills that underlie foreign language reading acquisition appear to have a universal influence, the influence of most cognitive skills is language specific, such that the skills that most strongly affect foreign language reading acquisition differ across languages.

Some findings in the current study require further clarification. First, in all three foreign languages, nonalphanumeric RAN had a larger contribution to reading development than alphanumeric RAN. Although this difference was only noteworthy in Chinese, it is at odds with previous research on reading in the native language, showing larger relations for alphanumeric than nonalphanumeric RAN in readers of both alphabetic and nonalphabetic orthographies (Araujo et al., 2015; Song et al., 2016). Also in the current study, literacy in the native Dutch language was somewhat more strongly related to alphanumeric than nonalphanumeric RAN. This observation raises the question whether the RAN-reading relationship is different for native and foreign languages. The current findings suggest that alphanumeric RAN is most important for learning to read in the native language whereas nonalphanumeric RAN plays a larger role in foreign language reading acquisition, especially in Chinese. It has been suggested that alphanumeric and nonalphanumeric RAN reflect distinct cognitive processes (Cummine, Szepesvari, Chouinard, Hanif & Georgiou, 2014; Misra, Katzir, Wolf & Poldrack, 2004). Nonalphanumeric RAN, object naming in particular, has been assumed to reflect efficient access to semantic information (Humphreys, Riddoch & Quinlan, 1988; Poulsen & Elbro, 2013), whereas alphanumeric RAN, specifically letter naming, has been related to the ease of access to phonology (Poulsen & Elbro, 2013). Accordingly, our findings show that although the contribution of nonalphanumeric RAN to word reading in the foreign languages is substantial, it does not contribute uniquely in any of the foreign languages, and may thus reflect general rather than reading specific processes. The interpretation of nonalphanumeric RAN as reflecting more general cognitive processes fits well with the idea that it relates to semantic processing, since semantic reasoning is related to verbal intelligence. Efficient access to semantics may be more important for readers of foreign orthographies than for native speakers, since the former have not yet established reliable phonological representations of the words they read. With respect to alphanumeric RAN, our findings indicate that although its contribution to foreign language word reading is relatively small, it is specific. That is, alphanumeric RAN is uniquely involved in Spanish reading development once nonalphanumeric RAN is left out of the analyses. In addition, alphanumeric RAN contributes (somewhat) more strongly than nonalphanumeric RAN to word reading in the native language. This suggests that alphanumeric RAN may be especially important for word reading in situations where phonological representations are either well established (in the native language) or easily acquired (in a transparent orthography like Spanish), a suggestion well in line with the idea that alphanumeric RAN reflects the ease of access to phonology.

Second, the contribution of verbal memory to word reading in each of the foreign languages was modest, even when controlling for the low reliability of this task. Interestingly, however, the relation with word reading in foreign languages was primarily attributable to the backward span task, whereas the influence of forward span appeared to be minimal. This suggests that working memory, the simultaneous storage and processing of information (Daneman, 1987), plays a role in foreign language reading acquisition, whereas short-term memory, i.e., the temporary storage of information (Swanson, 1994), does not. Although research on reading development in the native language has also indicated working memory as more important than short term memory (Gathercole, Alloway, Willis & Adams, 2006; Swanson, 1994; Swanson & Jerman, 2007), it is generally argued that both memory functions are involved in reading (Swanson & Howell, 2001; Swanson et al., 2009). The relative importance of working memory over short term memory for reading development in a foreign language could indicate that reading a word in a foreign language requires not only the accurate storage and retrieval of the representation of this word, but also the suppression of representations of the same word or related words in the native language. In accord with this suggestion, working memory capacity has been shown to be larger in individuals who master two languages than in monolinguals (Adesope, Lavin, Thompson & Ungerleider, 2010).

Third, intelligence appeared to play an important role in reading acquisition in all three foreign languages studied. The importance of verbal intelligence is in accordance with previous research that reported an effect of vocabulary on reading development, both in the native language (Nation & Snowling, 2004; Ouelette, 2006; Ziegler et al., 2010) and in a foreign language (Lindsey et al., 2003; Manis et al., 2004). However, the effect of nonverbal intelligence on reading development is less documented. The nonverbal intelligence tasks were included based on literature on Chinese reading in native speakers, suggesting their importance for reading development in the visually complex Chinese writing system (Ho & Bryant, 1999; Huang & Hanley, 1995; Siok & Fletcher, 2001). The current study thus extends this literature by showing that visual processing and reasoning skills are relevant for the development of Chinese reading skills in readers of alphabetic orthographies who learn Chinese as a foreign language as well. Surprisingly, our findings suggest that nonverbal intelligence is also involved in reading development in the foreign alphabetic languages Spanish and French. Since there was no correlation between nonverbal intelligence and Dutch reading proficiency, the contribution of nonverbal intelligence to reading seems to apply exclusively in foreign languages. These results suggest that foreign language learning, similar to other academic tasks, appeals to broad abilities related to the acquisition of new knowledge and skills. Alternatively, nonverbal intelligence may not contribute specifically to reading development in foreign orthographies, but rather to the first stages of reading development. In line with this assumption, nonverbal intelligence was also found to be involved in early reading development in the native language (de Jong & van der Leij, 1999).

Although our study of the skills underlying word reading acquisition in foreign morphosyllabic as well as shallow and deep alphabetic orthographies expands our insight in reading development in foreign languages, certain characteristics of the study design may limit the interpretation and generalization of results. First, the participants in the current study were followed throughout the first school year of foreign language learning. Obviously, the process of learning to read in a foreign language spans across multiple years. Consequently, the findings in the current study apply specifically to the first stages of the foreign language learning process. Previous findings have shown that in reading development in the native language the relative importance of cognitive predictors changes when reading proficiency increases. For example, in alphabetic orthographies, phonological awareness, letter-sound knowledge and verbal memory seem to be most important for initial reading acquisition (de Jong & van der Leij, 1999; Caravolas et al., 2013; Siegel, 1994; Vaessen et al., 2010), whereas the contribution of RAN may increase during reading development (de Jong & van der Leij, 1999; Caravolas et al., 2013; Vaessen et al., 2010). In addition, it has been suggested that in Chinese readers, phonological awareness at the syllable level is important during the first stages of reading development, whereas the influence of phoneme awareness increases when readers become more proficient (Newman, Tardif, Huang & Shu, 2011; Shu, Peng & McBride-Chang, 2008, but see Song et al., 2016). This pattern of findings raises the question of whether the relations between cognitive predictors and foreign language literacy skills that were found in the current study would be the same during later stages of foreign language acquisition.

Second, all reading tasks used in the current study contained a time limit. Consequently, findings relate only to reading fluency, not to accuracy. The time limit was employed partly because of time restrictions on test administration, but mainly because fluency tasks suited our research interest better. That is, fluency tasks have been shown to discriminate better between good and poor readers in transparent orthographies than accuracy once grapheme-phoneme correspondences are mastered (de Jong & van der Leij, 2003, Seymour et al., 2003).

Since our participants were fluent readers of Dutch, and there is considerable overlap between grapheme-phoneme correspondences across alphabetic orthographies, they can be expected to quickly read highly accurate, especially in the transparent Spanish orthography.

Third, morphological skills were not included as possible predictor skill in the current study, although research in native readers has indicated that morphological skills play an important role in Chinese reading development (Yeung et al., 2011; McBride-Chang et al., 2003). These skills were not included because morphology in Dutch is very different from Chinese, and it was thus expected to be of little importance. It therefore remains unclear whether morphological skills are also involved in Chinese reading development when Chinese is learned as a foreign language.

Last, since the participants in the current study were all attending the same high school, the sample could be considered selective. Intellectual functioning and social economic status were on general above average. In addition, although the participants were novices in the foreign languages under study, they all mastered at least one other foreign language (English). About half of the children even mastered one or two additional foreign languages at the time they started to learn Spanish, French and Chinese. Mastering multiple foreign languages is common in The Netherlands, as well as in many other parts of the world (Cenoz, 2013). However, it is unknown to what extent the results of the current study can be generalised to foreign language acquisition in individuals without prior knowledge of other foreign languages. Previous research suggests that the processes involved in foreign language acquisition are different for persons that learn a foreign language for the first time than for those who already gained skills and knowledge in another foreign language, although the exact nature of the influences of L2 experience on L3 learning are still unclear (Adesope et al., 2010; Bérubé & Marinova-Todd, 2012; Cenoz, 2013; Dewaele, 2001; Haenni, Hoti, Heinzmann, Müller, Oliveira, Wicki, & Werlen, 2011; Hammarberg 2001).

To conclude, the contribution of native language and underlying cognitive skills to reading acquisition in a foreign language seems for the most part language specific and influenced by both writing system and orthographic depth. Specifically, when native speakers of a language with a transparent alphabetic orthography learn to read in another transparent alphabetic orthography, they seem to mainly rely on their native language skills to accommodate knowledge about the new orthography. However, when the foreign orthography employs more complex letter-speech sound mappings, phonological processing skills and verbal intelligence become more important. This suggests that when children cannot rely on the letter-sound connections that they have internalized from their native language, they have to use their broader linguistic knowledge and academic thinking strategies to get a grip on the language's orthographic structure. Furthermore, when reading skills are acquired in a nonalphabetic writing system, not only verbal but also nonverbal intelligence and visual processing speed are addressed, and intelligence becomes the most prominent contributor. This implies that when a foreign language is represented with visually complex characters, visual and reasoning skills become important in encoding these characters and distinguishing one from another.

These findings have implications of interest to both society and science. Societally, the finding that different patterns of cognitive skills are related to reading proficiency in different foreign languages may be informative for students and their teachers, when they have to choose which foreign language they will study. For example, the current data suggest that children with strong phonological skills are likely to achieve high reading proficiency in foreign languages with alphabetic orthographies. Contrarily, children with poor phonological skills and naming speed but adequate reasoning and visual skills, including many children with dyslexia, may expect greater academic success when learning a nonalphabetic orthography. The current findings are also supportive of a teaching approach aimed at metalinguistic awareness (Cenoz, 2013). That is, making students aware of the commonalities and differences between languages, may aid in the transfer of language skills across languages or in determining the most efficient learning strategy. Scientifically, findings in the current study add to the 'universal science of reading' (Perfetti, Cao & Booth, 2013). They support the assumption that both universal and language specific elements are involved in foreign language acquisition (Geva & Siegel, 2000; Saiegh-Haddad & Geva, 2010), although the influence of specific characteristics of the foreign language seems dominant (Koda, 2007).

Chapter 6

General discussion

The main aim of the current thesis was to improve our understanding of the development of reading fluency, by focusing on the cognitive and affective mechanisms that underlie both successful and failing reading fluency development. To this end, four studies were conducted. The first two studies (chapter 2 and 3) addressed the timing of orthography-phonology integration during word reading in skilled and developing readers. Subsequently, in chapter 4, we examined the impact of phonological processing skills and feelings of uncertainty on reading fluency in typical reading and dyslexic children. Finally, chapter 5 focused on the cognitive skills that are involved when children acquire reading fluency in a foreign orthography. Below, the main outcomes of the studies will be summarized and implications of the findings for current theories on reading as well as for the clinical practice of educators will be discussed.

Timing of orthography-phonology integration during word reading

It has become increasingly clear that the integration of letters and their accompanying speech sounds constitutes a crucial component of reading skill (Foulin, 2005), specifically of reading fluency (Blau, van Atteveldt, Ekkebus, Goebel & Blomert, 2009; Blau et al., 2010). In addition, recent accounts of dyslexia postulate that a deficit in orthography-phonology integration forms a primary and proximal cause of the dysfluency that characterizes dyslexic readers (Blomert, 2011, Gullick & Booth, 2014; Hahn, Foxe & Molholm, 2014). Specifically, it has been suggested that dyslexic readers are hampered by impaired timing in the activation of orthographic and phonological information during reading (Breznitz, 2002; 2006; Breznitz & Misra, 2003). However, the exact timing of orthography-phonology integration during reading development in Dutch readers is thus far unknown. Therefore, in order to enhance our insight into the nature of letter-speech sound integration processes, in chapters 2 and 3 we examined the timing of orthographic and phonological activation during word reading in skilled and developing Dutch readers.

Summary of research findings

The first study (chapter 2) investigated how quickly skilled readers can activate orthographic codes during reading, and how quickly these orthographic codes are subsequently translated into phonological codes in order to access word meaning. A difficulty in the study of orthography-phonology integration is that after the initial phases of reading instruction, this process occurs highly rapidly and without full awareness of the reader. Therefore, in both chapter 2 and 3, we adopted a research method that allows studying such rapid processes: masked priming (Forster & Davis, 1984). In reading research, masked priming involves the presentation of a target word, which is preceded by a briefly presented and masked prime word. Since the prime word is presented so briefly and still effects target word recognition, its influence must occur during the very first stages of the word recognition process (Forster, Mohan & Hector, 2003). Masked priming has been used successfully to identify time courses of orthography and phonology activation in skilled readers of the opaque French orthography (Ferrand & Grainger, 1992; 1993; 1994). We aimed to clarify to what extent the timing of the activation of orthographic and phonological representations differs between skilled readers of Dutch and French, and thus whether these time courses are influenced by the orthographic depth of the orthography that is read. We presented phonological, orthographic and control primes at 33, 50, 67 and 83 ms to investigate the first stages of the word recognition process. Facilitation in word recognition fluency brought about by the phonological prime in comparison to the orthographic prime was referred to as phonological priming. Facilitation in word recognition fluency induced by the orthographic prime as compared to the control prime was identified as orthographic priming. Results indicated that when stimuli were typical Dutch words, orthography and phonology were so strongly interconnected that orthographic primes provided intertwined orthographic and phonological facilitation. Consequently, limited room was left for additional facilitation by the phonological prime. However, when stimuli were specifically selected to allow for large phonological differences between the orthographic and phonological prime, time courses of orthographic and phonological processing could be distinguished. Orthographic primes facilitated word recognition only at the shortest prime exposure duration of 33 ms, and phonological priming effects became apparent from 50 ms onwards. These findings suggest that strong phonological differences are a prerequisite to separate phonological from orthographic priming effects. When phonological differences are strong enough, it becomes clear that orthographic and phonological priming follow distinct time courses. Orthography is accessed initially yet orthographic codes are quickly translated into phonological codes with phonological influences dominating the remainder of the lexical access stage.

When the time courses of skilled Dutch readers in chapter 2 are compared to those reported for skilled readers of the opaque French orthography (Ferrand & Grainger, 1993) it can be noted that, despite strong similarities between the time courses in the two orthographies, phonology seems to be accessed slightly earlier in Dutch than in French. That is, in Dutch, phonological influences outperform orthographic influences from 50 ms onwards, whereas in French phonology becomes dominant at 67 ms. This difference should be interpreted with caution, since it is rather small, and it is unclear to what extent it is influenced by differences in the stimulus material. Yet, it is tentatively suggested that the translation of orthographic representations into phonological representations occurs earlier in transparent than opaque orthographies.

The time courses of orthography and phonology activation in skilled Dutch readers that were portrayed in chapter 2 identified how quickly orthographic representations could be accessed and translated into phonological codes in readers who had fully integrated orthography-phonology associations. Subsequently, in chapter 3, we investigated how these orthography-phonology associations develop when children are learning to become fluent readers. To this end, we used the same masked priming paradigm as in chapter 2 with children who were beginning (grade 2), intermediate (grade 4) and advanced (grade 6) readers. Results showed clear orthographic priming effects in children of all three age groups. With increasing levels of reading proficiency, orthographic priming became facilitative at increasingly short durations. However, phonological priming effects were absent. Unlike our findings in adults, the absence of phonological priming effects was not due to the subtleness of the phonological differences between orthographic and phonological primes. Even with the use of stimuli with large phonological differences, phonological priming could not be detected in any of the three age groups. In fact, large phonological differences resulted in the absence of phonological as well as orthographic priming effects.

Results thus indicate that already after 1,5 year of reading instruction, children can access orthographic representations during the early lexical access stage of the word recognition process, of which they are not fully aware. During reading development, orthographic codes become increasingly early accessible, suggesting increasing automatisation. In contrast, phonological representations do not seem to be accessed during the lexical access stage of word recognition. Clearly, the interpretation of null results is always speculative, but the absence of phonological priming effects might indicate that phonological processes are not yet automatized in 2nd to 6th grade readers, and that automatic phonological processing emerges later in development.

Implications for theories of reading

The finding that in skilled readers, orthographic representations are rapidly translated into phonological representations and phonological influences dominate the remainder of the lexical access stage, support so called 'strong phonological' theories of visual word recognition. That is, in the field of reading research, opinions differ with respect to the role of phonology in visual word recognition. The 'weak phonological' perspective (Coltheart, Rastle, Perry, Langdon & Ziegler, 2001) on this issue is based on the dual-route theory that was mentioned in chapter 1. It postulates that the recognition of written words is driven primarily by the direct pathway that is based on an analysis of orthographic word characteristics. Phonology only plays a role through the indirect pathway. Along this pathway phonological decoding is employed when direct recognition is not possible, as may occur with unfamiliar words. Phonological analysis is thus considered a slow process, which is secondary to orthographic processing and nonessential for retrieving correct word meaning of familiar words. In contrast, 'strong phonological' theories (e.g., Drieghe & Brysbaert, 2002; Frost, 1998; 2005; Lukatela & Turvey, 1994) assume that the activation and analysis of phonological word information is dominant and essential in visual word recognition. According to these theories, orthographic representations are rapidly translated into phonological representations, and these phonological representations support visual word recognition (Rastle & Brysbaert, 2006). Our findings add to previous masked priming results (e.g. Carreiras, Perea, Vergara & Pollatsek, 2009; Ferrand & Grainger, 1993; Grainger, Kiyonaga & Holcomb, 2006) showing that the translation of orthographic into phonological representations occurs rapidly, and takes place during the first stage of the word recognition process, that readers are not fully aware of. These findings are thus in line with a rapid and obligatory nature of phonological processing during visual word recognition. Our study indicates that this quick and essential role of phonology is also applicable to skilled word reading in the Dutch orthography.

Comparing the time courses of the skilled readers of the transparent Dutch orthography in chapter 2 with those previously reported for skilled readers of the opaque French orthography (Ferrand & Grainger, 1993), allowed investigating the impact of orthographic depth on the timing of orthographic and phonological component processes during visual word recognition. As noted, the result of this comparison should be interpreted with caution, since results may be influenced by differences in the choice of stimuli. In fact, in chapter 3 the time point at which orthographic priming first appears differs between study 1 and study 2, which manifests the impact of the stimulus material on time courses. However, if we do tentatively interpret the finding of earlier activation of phonology in Dutch than in French readers, we can conclude that it is in line with the Orthographic depth hypothesis (Frost, 1998; 2005). Hence, it supports the view that the straightforward correspondences between orthographic and phonological codes in transparent orthographies allow lexical access to be based on a more detailed phonological representation than in opaque orthographies. However, our findings do not rule out alternative interpretations. For example, the phonological grain size hypothesis (Ziegler & Goswami, 2005) assumes that readers of transparent orthographies form orthography-phonology connections for small 'grain sizes' such as individual letters or graphemes. In contrast, readers of opaque orthographies rely on larger grain sizes, such as syllables or whole words. It could be argued that the translation of orthographic to phonological representations occurs more rapidly for small than large grain sizes. More research is thus clearly needed in order to fully understand the impact of orthographic depth on the timing and nature of orthography-phonology integration.

In developing readers, it was shown that orthographic codes become increasingly early accessible during development. This finding is in line with previous findings, indicating that although readers of transparent orthographies achieve high levels of accuracy within the first year of reading instruction, reading fluency continues to improve afterward and the road to fully automatized reading is in fact rather long (Vaessen & Blomert, 2010). Our findings extend this theory by showing that not only the reading speed, but also the underlying access to orthographic representations becomes increasingly rapid. This suggests that after the initial formation of orthography-phonology connections, an important and long-lasting phase in reading development entails the fine-tuning of these connections into easily accessible representations. It could therefore be assumed that Ehri's final 'consolidated phase' of reading development (Ehri, 2005), in fact also comprises an 'automatised phase'. Findings thus fit well with the premise of the lexical quality hypothesis that representations become of increasingly high quality, as reflected in close interconnectivity and easy retrievability (Perfetti, 2007; Perfetti & Hart, 2002).

The results on phonological priming in developing readers could be interpreted to indicate that neither beginning, intermediate nor advanced elementary school readers had automatized phonological processes. This finding, although somewhat unexpected, is in line with dual-route models of reading (Coltheart, Curtis, Atkins & Hailer 1993; Coltheart et al., 2001), thereby supporting the assumption that phonological recoding is slow and effortful, and does not yet occur during the early stages of word recognition. However, it should be noted that our finding of early access to phonological representations in adult readers is not in accordance with dual-route theory. That is, dual-route models assume that phonological recoding is not only slow in developing readers, but also in proficient readers, since phonological recoding occurs only when direct orthographic access does not succeed in retrieving the correct lexical representation. Our findings, in contrast, suggest that phonological processing is not slow in general, but rather needs time to become automatically accessible. In agreement with the assumption that automatisation of reading skills is a long-lasting process (Vaessen & Blomert, 2010), automatisation of orthography-phonology integration seems not to have been completed in 6th grade, but seems to continue into adolescence. This begs the question of how reading fluency and underlying orthographic and phonological processes develop during adolescence. Future studies in this area are required to address this question, as the period between elementary school and adulthood has thus far received relatively limited attention from reading researchers.

The absence of phonological priming effects in developing readers prevented identifying the timing of orthography-phonology integration during reading development in typical readers. Although the suggestion that phonological processes are not yet automatized in 2nd to 6th grade readers is interesting for theories of reading development, findings could thus not serve as a reference point for future studies to compare the timing of orthography-phonology integration between normal reading and dyslexic children. It therefore remains unclear whether the access of orthographic codes and the subsequent connection between orthographic and phonological codes is delayed in children with dyslexia. Our findings suggest that the masked priming paradigm may not be sufficiently sensitive to study the timing of orthography-phonology integration in developing readers. Possibly, the ERP technique can provide more fine-grained analyses of time courses, since ERP's can be measured with high temporal resolution (Luck, 2005).

In fact, previous ERP studies did already provide valuable insights in the timing of orthography-phonology integration in dyslexic readers. An interesting series of experiments showed that when normal reading children processed either speech sounds (auditory condition) or letters and speech sounds (audiovisual condition), an enhancement in the early mismatch negativity (MMN) ERP component was observed during audiovisual processing. This indicated that the visual letters had interacted with the speech sounds pre-attentively. However, in dyslexic children, this enhancing effect of letters on speech sound processing was absent. Instead, the dyslexic readers showed a modulating effect of letters on speech sounds in a much later ERP component, the so called late discriminant negativity or LDN. The authors interpreted the MMN effect as an indication of automatic letter-speech sound integration, and the LDN effect as the mere association of letters and speech sounds (Froyen, Bonte, Van Atteveldt & Blomert, 2009; Froyen, Willems & Blomert, 2011).

In addition to the finding of deviant orthography-phonology integration in dyslexic readers at the level of individual letters, other studies report electrophysiological evidence for inefficient orthography-phonology integration at the word level that is more related to reading in daily life. In accordance with the asynchrony hypothesis that was mentioned in chapter 1, Breznitz and colleagues (Breznitz, 2002, 2003; Breznitz & Meyler, 2003; Breznitz & Misra, 2003; Meyler & Breznitz, 2005) reported that both children and adults with dyslexia showed delayed latencies of the P200 (assumedly related to sensory stages of encoding) and P300 (assumed to indicate task related decision making) ERP components during phonological and orthographic processing of visual words. Both typical and dyslexic readers showed a gap between the latency of phonological and orthographic processing. However, this gap was found to be enlarged in dyslexic readers, in the P200 as well as the P300, and gap sizes were related to word reading performance (although in Breznitz (2003) this was true only for the P300 gap size). This supports the assumption that timing of orthography-phonology integration is a factor that underlies reading ability, and that this timing is impaired in dyslexic readers.

An ERP component that is assumed to specifically relate to the integration of orthographic and phonological representations is the N300 (Bentin, Mouchetant-Rostaing, Giard, Echallier & Pernier, 1999; Penolazzi, Spironelli, Vio & Angrilli, 2006; Simon, Bernard, Largy, Lalonde & Rebai, 2004). Dyslexic children were reported to show deviances in the distribution of the N300 amplitude during crossmodal (auditory-visual) word processing, but not during unimodal (visual-visual) word processing. During crossmodal word processing, the N300 was left lateralized in typical readers, but bilaterally distributed in dyslexics, and N300 lateralization was related to word reading fluency (Hasko, Bruder, Bartling & Schulte-Körne, 2012). Although this study did not find neurophysiological evidence for a delay in orthography-phonology integration amongst dyslexic children, it did indicate deviant visual word processing in dyslexic children when orthographic and phonological word information needed to be integrated. The deviancy occurred at the point in time where orthographic and phonological information is integrated. Altogether, these ERP studies thus support the assumption of impairments in the timing of orthography-phonology integration in dyslexic readers. Future ERP studies may thus further delineate the timing of access to orthographic codes and the subsequent coupling between orthographic and phonological codes in children with dyslexia.

Implications for clinical practice

For educators, the most interesting finding of our studies on orthography-phonology integration is probably that orthography-phonology integration seems to not yet be fully automatized in 6th grade. This suggest that the process of reading development is not finished at the end of elementary school, but that reading skills continue to automatize during secondary school. However, curricula of secondary education do generally not include instruction on reading. In fact, already from grade 4 in elementary school onwards, the focus shifts from ‘learning to read’ to ‘reading to learn’. This means that exercises are not selected with the aim of enhancing children's reading proficiency, but to gain knowledge about a certain topic (e.g. geography, history or mathematics) by means of reading. In this way, children are still frequently exposed to text, and receive practice in reading. However, the current findings raise the question whether this practice is optimal, or even sufficient, for all children. If an important stage of reading development, the automatisation of orthography-phonology integration to achieve quick and effortless word recognition, is still in progress, more explicit instruction or guidance may be helpful. This instruction may be beneficial to all children, or specifically to the poorer readers or to children who are not intrinsically motivated to read and thus gain limited reading experience.

Unfortunately, little is known about reading development and its underlying processes in adolescents, since reading researchers generally focus either on children or adults. Further research is therefore necessary to enhance our knowledge about the development of reading skill, the automatisation of component processes, and the effects of various teaching strategies during adolescence. For now, current results can make educators of secondary school students aware that their pupils' reading processes may not yet be optimal and thus that delays in the automatisation of the reading process could be a possible source of educational difficulties.

Feelings of uncertainty in children with dyslexia

Efficiency of orthography-phonology integration is certainly not the only factor underlying reading fluency and deficits in orthography-phonology integration are not the only causal factors of the reading fluency problems of children with dyslexia that have been proposed. In fact, according to the multiple deficit model, multiple risk and protective factors interactively influence a person's vulnerability to develop dyslexia (e.g. Moll, Loff & Snowling, 2013; Pennington, 2006). The risk factors that have thus far been assumed to be involved generally encompass deficits in cognitive skills, with deficits in phonological processing skills being the best established. We aimed to identify whether affective factors, specifically uncertainty, contribute to dyslexics' dysfluent reading as well. To this end, in chapter 4 we used diffusion modelling (Ratcliff & McKoon, 2008; Vandekerckhove & Tuerlinckx, 2007; 2008), to investigate the influence of phonological processing deficits and uncertainty on word recognition in dyslexic children. We applied the diffusion model to data that emerged from a lexical decision paradigm. As such, the model describes the decision process, in which a reader decides whether a letterstring is a real word or a nonword. We focussed on three components of the model: The drift rate describes how quickly information about word characteristics (including phonology, orthography and semantics) from the letterstring accumulates in order to make a decision. The boundary separation reflects the amount of evidence that a reader needs before a decision is made, and can thus be interpreted as a certainty criterion. Non-decision time consists of all processes other than the decision process, including encoding and response execution. We studied not only visual word recognition, but also auditory word recognition as it has been suggested that the phonological deficits render dyslexic children at risk for word recognition problems in the auditory domain as well (Bradlow, Kraus & Hayes, 2003; Ramus, White & Frith, 2006; Rosen, 2003; Ziegler, Pech-Georgel, George & Lorenzi, 2009).

Summary of research findings

Behavioural findings indicated that the children with dyslexia were impaired in word recognition in both the visual and auditory domain, in comparison to typical reading age mates. Their visual word recognition was both slower and less accurate, their auditory word recognition was equally fast but less accurate. Diffusion model results showed that the impairments in visual word recognition could be accounted for primarily by a delay in the accumulation of word characteristics, which include phonological processing. The impairments seemed to be exacerbated by the adoption of elevated certainty criteria, indicating that heightened uncertainty hampered the dyslexic children in their word recognition performance as well. The inaccurate auditory word recognition also resulted from delays in the accumulation of word characteristics. However, dyslexic and typical readers did not appear to set different boundary widths, suggesting that uncertainty does not hamper dyslexic children when recognizing auditory words.

Implications for theories of reading

The finding that the word reading difficulties of children with dyslexia are caused by underlying phonological processing deficits is in line with the phonological processing deficit hypothesis (Snowling, 1998; Vellutino, Fletcher, Snowling, & Scanlon., 2004) and thereby adds mathematical evidence to an extensive body of research supporting this hypothesis (i.e. Catts, 1993; de Jong & van der Leij, 2003; Elbro, Borstrøm & Petersen, 1998; Goswami, 2002; Snowling, 2000; Stackhouse & Wells, 1997; Stanovich & Siegel, 1994; Ziegler, Perry, Ma-Wyatt, Ladner & Schulte-Körne, 2003).

However, findings suggest that the impact of the phonological processing deficits is exacerbated by uncertainty in children with dyslexia. Previous research indicated that children with dyslexia are at increased risk for developing emotional problems, including uncertainty, stress, worries and low self-esteem (Alexander-Passe, 2007; 2008; Ingesson, 2007). It is generally assumed that these emotional problems are the result of the repeated academic failure that children with dyslexia experience. Yet, the current findings suggest that heightened levels of uncertainty are not only a consequence but also a cause of the word reading difficulties (see also Morgan, Farkas, Tufis & Sperling, 2008). This would indicate that the relation between reading and emotional problems is bidirectional in dyslexic children. Possibly, the emotional problems initially emerge as a consequence of difficulties with reading and related academic tasks, but in turn these emotional problems may further reduce reading fluency, thereby leading to a vicious circle.
Findings also provide support for the assumption that the phonological processing deficits of children with dyslexia render them impaired in auditory word recognition, specifically in recognizing speech sounds under background noise (Boets, Ghesquière, van Wieringen &

Wouters, 2007; Wible, Nicol & Kraus, 2002; Ziegler et al., 2009). That is, dyslexic children may be impaired in translating phonetic features of the speech signal into distinct and stable phonological representations.

With respect to the multi deficit account of dyslexia, the findings of chapter 4 suggest that not only cognitive, but also affective factors should be included as potential risk and protective factors for developing dyslexia. Specifically, uncertainty seems to aggravate the severity of the reading problems that result from phonological processing deficits. This would entail that two children with the same degree of phonological impairment could achieve different levels of reading skill, dependent on the extent to which they suffer from additional emotional problems. Clearly, our results only pertain to group level comparisons. Future studies are required before conclusions about the impact of emotional problems in individual children are possible. It should be noted that deficits in speech perception in noise could also be considered as a possible risk factor for the development of dyslexia. In fact, speech-in-noise perception has been shown to predict reading proficiency in children with dyslexia (Ziegler et al., 2009). In the current study, speech perception in noise was not explicitly tested as an underlying factor of visual word recognition. However, correlational results could not provide evidence for a relation between word reading fluency and either speed (r=.24, p= ns) or accuracy (r=.03, p= ns) of speech in noise perception. Since the contribution of auditory processing deficits to dyslexia is generally controversial (Ramus, 2003; Rosen, 2003), future studies on the impact of speech-in-noise perception on the development of dyslexia seem necessary before conclusions about its status as risk factor can be drawn.

Implications for clinical practice

Our conclusion that uncertainty may further hamper the development of reading fluency in children with dyslexia could have implications for the support provided to dyslexic pupils, both in schools and treatment settings. Although the finding is based on just two experiments, and results of one experiment show only a trend towards significance, it suggests that children with dyslexia benefit from support aimed at their emotional functioning. This support can be provided both in the classroom and in treatment sessions. Specifically, support in the classroom might have a preventive function, whereas support during treatment may reduce the severity of the emotional problems once they have surfaced. In this respect, a positive development is the recent inclusion of a guideline to provide psycho-education during dyslexia treatment in the Dutch protocol dyslexia (Nationaal Referentiecentrum Dyslexie, 2013). By enhancing dyslexic children's insight in dyslexia and teaching strategies to cope with its consequences, this psycho-education aims to ameliorate their emotional wellbeing.

In a small-scale study we investigated the impact of this added psycho-education training (Kloet, Zeguers & Kappenburg, unpublished thesis; Zeguers & Snellings, 2016). We first examined whether children with dyslexia actually suffer from emotional problems. Results indicated that before the start of treatment, children with dyslexia reported similar levels of effort for reading activities as their non-impaired classmates. However, marked differences appeared in their motivation to perform this effort. Typical readers read more often than dyslexic readers because they enjoyed it or to relax and escape from reality, and consequently experienced higher levels of reading pleasure. In contrast, dyslexic readers read more often than typical readers because they felt obliged to do so. They experienced pressure to read, both external pressure from their parents and teachers as well as internal pressure from their own feeling that they had to practice their reading skills in order to achieve appropriate academic performance. The children with dyslexia considered reading performance more important for academic success than their typical reading peers, but had less confidence in their ability to achieve adequate levels of reading skill. These findings thus support the assumption that children with dyslexia experience heightened levels of emotional problems and advocate for the inclusion of a training in coping with these emotional problems in the treatment of dyslexia.

We then went on to investigate the effect of the psycho-education module in the dyslexia treatment on dyslexic children's emotional functioning. Results showed that after the first three months of treatment, dyslexic children who received dyslexia treatment without psycho-education read less often than before the treatment because of external and internal pressure. Dyslexic children who received dyslexia treatment with psycho-education read more often because they enjoyed it, experienced more reading pleasure and felt more confident with respect to their reading skills. Although these results are based on small sample sizes and cover only the first three months of the dyslexia treatment, they tentatively suggest that the inclusion of psycho-education has a positive effect on the emotional wellbeing of children with dyslexia. For educators this suggest that they may be able to support children with dyslexia more broadly by training not only reading and reading related cognitive skills, but also offering training at the emotional level. The results also raise the question, whether the ameliorated emotional functioning of the dyslexic children also resulted in improved reading fluency. Unfortunately, these data are not available. Future studies are therefore necessary to assess the effect of psycho-education during dyslexia treatment on both emotional functioning and improvement in reading fluency.

Dyslexia and learning to read in a foreign orthography

In the Netherlands, children do not only learn to read in their native language, but in time also in one or more foreign languages. This comprises a new challenge for children with dyslexia, since the acquisition of reading skills in a foreign language is assumed to build unto native language component skills which include phonological skills (Sparks & Ganschow, 1991). Hence, the poor phonological skills of dyslexic children render them vulnerable to reading difficulties when acquiring a foreign language (Ganschow, Sparks & Schneider, 1995). This raises the question whether the severity of the reading problems that children with dyslexia experience during foreign language learning differs across languages, and depends on the importance of phonological processing for learning to read in the foreign language concerned. This question constituted the starting point of the study reported in chapter 5.

Insight in the similarities and differences between orthographies with respect to the processes (including phonological processes) that contribute to successful reading acquisition in foreign language learners appeared to be rather limited, especially concerning the acquisition of reading skills in foreign nonalphabetic orthographies. Given the scarcity of knowledge on the degree to which skills underlying foreign language acquisition are influenced by characteristics of the specific orthography, we decided to first investigate these underlying skills in languages with contrasting orthographic characteristics in typical readers. This insight in correlates of foreign language reading development in typical readers may subsequently serve as a basis to explore how children with dyslexia learn to read in different foreign languages. To this end, in chapter 5 we studied which language and cognitive skills are involved when adolescents who are proficient readers of a transparent alphabetic orthography (Dutch) simultaneously learn to read in three foreign languages with a transparent alphabetic orthography (Spanish), an opaque alphabetic orthography (French) and a non-alphabetic writing system (Chinese).

Summary of research findings

Findings indicated that the cognitive skills that were most important for word reading development differed between the three foreign languages. Spanish reading development was shown to depend most strongly on native language reading skills. Cognitive skills, most notably phonological awareness and verbal intelligence, contributed only because of their influence on native language reading. In contrast, French reading acquisition was mainly influenced by phonological awareness and verbal intelligence, and Chinese reading acquisition by verbal as well as nonverbal intelligence. Findings thus suggest that when native speakers of a language with a transparent alphabetic orthography learn to read in another transparent alphabetic orthography, they seem to build their knowledge about this new orthography mainly on the reading skills that they already possess in their native language. However, when the foreign orthography employs more complex letter-speech sound mappings, they can no longer rely on the letter-sound knowledge that they have internalized from their native language, and have to use broader linguistic knowledge and reasoning to become acquainted with the orthographic structure of the new language. When reading skills are acquired not in the familiar alphabetic writing system, but in visually complex characters, visual and reasoning skills become important for encoding these characters and distinguishing one from another. In addition to these differences between the languages, there were also two skills, rapid naming and intelligence, that appeared to contribute to reading development in all three foreign languages. Findings thus suggest that although some of the cognitive skills that underlie foreign language reading acquisition appear to have a universal influence, the influence of most cognitive skills is language specific, such that the skills that most strongly affect foreign language reading acquisition depend on characteristics of the language concerned.

Implications for theories of reading

With respect to theories on the acquisition of reading skills in a foreign language, the findings of chapter 5 contribute to a central issue in the field of research on foreign language learning, namely whether the skills that underlie foreign language reading acquisition are universal or language specific. Our finding that the skills that are most strongly involved in foreign language reading acquisition are to a large extent different between orthographies, is in line with the script-dependent hypothesis (Geva & Siegel, 2000; Geva & Wade-Woolley, 1998). This hypothesis suggests that the cognitive skills that contribute to foreign language reading acquisition depend on characteristics of the specific language that is to be learned. Our findings extend the basis of support for this hypothesis by showing that the language specificity of underlying cognitive skills also applies in a within-subject design in which all languages under study are acquired as foreign languages for all participants. This rules out possible effects of demographical, educational and emotional influences that could play a role in group comparisons.

Our findings may also expand the script-dependent hypothesis, by specifying two of the language characteristics that seem to affect the influence of underlying cognitive skills, i.e. orthographic depth and writing system. Orthographic depth seems to effect to what extent either reading skills or underlying cognitive skills in the native language are involved. That is, when skilled readers of a transparent alphabetic orthography are learning to read in another alphabetic transparent orthography, they can use the reading skills that they already developed in their native language to identify words in the new language. However, when the foreign language is more opaque, these native language reading skills do not suffice, and underlying phonological and language skills need to be addressed in order to crack the code of the new language's orthographic structure. Admittedly, on the basis of the current data it is impossible to specify whether this difference between transparent and opaque foreign orthographies is due to differences in the languages' orthographic depth as such, or to the degree to which the foreign language's orthographic depth is similar to the orthographic depth of the native language. That is, Spanish is not only more transparent, but also more related to Dutch, whereas French is both more opaque and more distant from Dutch. This issue should be addressed in future studies, but the current data at least suggest that orthographic depth is a linguistic characteristic that influences the degree to which underlying skills are involved in foreign language reading acquisition.

With respect to the influence of writing system, our findings suggest that both the contribution of phonological and visual processing skills is different in foreign morphosyllabic than foreign alphabetic orthographies, at least for native speakers of a language with an alphabetic orthography. Interestingly, these findings readily relate to a central question in the field of foreign language reading acquisition, namely whether the visual complexity of morphosyllabic characters (most notably Chinese) and the absence of a direct relation to phonemes, renders learning to read in Chinese less dependent on phonological processing skills (Huang & Hanley, 1997; McBride-Chang & Kail, 2002; Siok & Fletcher, 2001), and more on visual processing skills (Huang & Hanley, 1995; Siok & Fletcher, 2001) than learning to read in alphabetic orthographies. The findings of chapter 5 suggest that this question can be answered positively. Thereby, our findings contrast with research on Chinese reading development in native speakers, which generally indicates that phonological skills do play an important role (Ho & Bryant, 1997; McBride-Chang & Ho, 2000; McBride-Chang & Kail, 2002; Perfetti, & Zhang, 1991; Zhou, Duff & Hulme, 2015), whereas the contribution of visual skills is disputed (Ho & Bryant, 1999; Huang & Hanley, 1995; McBride-Chang, Chow, Zhong, Burgess & Hayward, 2005; Siok, Spinks, Jin & Tan, 2009; Tan, Spinks, Eden, Perfetti & Siok, 2005). This contrast might indicate differences in the development of Chinese reading skills between native speakers and foreign language learners who are not yet familiar with the morphosyllabic writing system. Since these readers are used to a writing system where visually simple letter symbols directly represent the phonemic structure of the language, and have to get acquainted with visually complex symbols for which the relation with speech sounds is either lacking or inconsistent, visual skills may be relatively important whereas phonological processing, at least at the phonemic level the readers are familiar with, is less effective.

The study described in chapter 5 was initially derived from the question whether the severity of the reading problems that children with dyslexia experience during foreign language learning differs across languages, and depends on the importance of phonological processing for learning to read in the foreign language concerned. Since our study did not include dyslexic children, we cannot yet answer this question. However, findings indicate that the degree to which phonology is involved in foreign language reading acquisition differs across languages. Specifically, phonological processing seems to be less important for learning to read in foreign languages with morphosyllabic orthographies than in foreign languages with alphabetic orthographies. When this finding is related to the Linguistic Coding Differences Hypothesis (Sparks & Ganschow, 1991), it may suggest that learning to read may be easier in foreign morphosyllabic orthographies than in foreign alphabetic orthographies for children with dyslexia who are used to read in an alphabetic orthography. That is, if the reading problems that children with dyslexia often experience during foreign language acquisition arise because their impaired phonological processing skills are addressed, these reading problems should be smaller during the acquisition of foreign morphosyllabic orthographies than foreign alphabetic orthographies. Clearly, this suggestion is highly speculative and calls for future studies to compare the acquisition of foreign language reading skills in typical reading and dyslexic children. The insight in the skills involved in foreign language reading development across orthographies in general, as described in chapter 5, may function as a starting point for these future studies.

Implications for clinical practice

Educators involved in foreign language education may be interested in the finding that the acquisition of reading skills depends on different underlying language and cognitive skills in different foreign languages. This suggests that different cognitive profiles are related to success in reading acquisition in different foreign languages. For example, the findings of chapter 5 suggest that children with strong phonological skills are likely to achieve high reading proficiency in foreign languages with alphabetic orthographies. In contrast, children with poor phonological skills and naming speed but adequate reasoning and visual skills, including many children with dyslexia, may expect greater academic success when learning a nonalphabetic orthography. This type of knowledge may thus be useful for students and their teachers when they have to choose which foreign language they will study. Here we should notice that the current study only provides the initial pieces of information for these types of decisions in educational practice. More extensive knowledge about a larger palette of potential contributing language and cognitive skills as well as a larger number of foreign languages and accompanying linguistic characteristics and different stages of the learning process is clearly required before it can be applied in decisions about the academic careers of individual children.

The finding that different foreign orthographies call upon different underlying skills for the development of reading fluency, may also have implications for remediation practices. Possibly, foreign language reading difficulties may call for different types of instruction and exercises in different languages. For example, Dutch students who experience reading difficulties in Spanish may benefit from exercises aimed to enhance their Dutch reading proficiency, whereas Dutch students that struggle with reading in Chinese may be better supported by training of their visual skills. Clearly this implication is only speculative at this point. However, given the importance of foreign language proficiency in the current international society, insight into the remediation of foreign language learning difficulties seems highly relevant. The current study may provide a basis for new experimental studies aimed at gaining insight in the optimisation of this remediation.

In all three foreign languages that were studied in chapter 5, reading development was related to language or cognitive skills in the native language. This is in line with the assumption that skills that underlie reading development in the native language 'transfer' to support foreign language development, in the sense that reading skills in the new language develop by drawing on skills that are already established in the first language (Genesee, Geva, Dressler & Kamil, 2006; Keung & Ho, 2009; Koda, 2007; Sparks, Patton, Ganschow & Humbach, 2009; van Gelderen et al., 2004; Verhoeven, 1994). This suggests that foreign language learners may be supported by the inclusion of metalinguistic awareness training in their curricula (Cenoz, 2013). Namely, once students become aware of the commonalities between their mother language and (either of) the foreign language(s) they study, they may be more likely to address skills and knowledge that they already established and use this to more efficiently acquire the new language(s).

General conclusion

The four studies that were presented in the current thesis have expanded our understanding of word reading fluency development in typical readers and children with dyslexia. They provided new insights in the timing of orthography-phonology integration underlying fluent reading as well as impaired reading fluency development, about the impact of uncertainty on the reading fluency impairment of children with dyslexia, and about the skills that underlie reading fluency development in foreign languages. Specifically, the thesis indicates:

- During the first stage of the visual word recognition process, Dutch skilled readers initially access orthography, yet orthographic codes are quickly translated into phonological codes. Phonological influences dominate the remainder of the lexical access stage.
- Phonology seems to be accessed slightly earlier in Dutch skilled readers than in French skilled readers.
- In typical Dutch words, orthography and phonology are highly interconnected. Therefore, in a masked priming experiment, strong phonological differences are required to separate phonological from orthographic priming effects.
- Developing readers with 1,5 year of reading experience can already access orthographic representations during the first, not fully conscious, lexical access stage of the word recognition process.
- During reading development, orthographic codes become increasingly early accessible, which suggests that orthographic access becomes increasingly automatized.
- Phonological processes seem not to be automatized yet in 2nd to 6th grade readers, which suggests that automatic phonological processing emerges later in development.
- The impairments in visual word recognition fluency that characterize children with dyslexia result primarily from underlying phonological processing deficits, and are exacerbated by uncertainty. This suggests that uncertainty may not only be a consequence but also a cause of dyslexic children's reading dysfluency.
- The phonological processing deficits of children with dyslexia render them impaired not only in visual, but also in auditory word recognition. This manifests in impaired recognition of speech sounds under background noise.
- When Dutch skilled readers learn to read in a foreign orthography, the cognitive skills that are most important for foreign language reading acquisition depend on characteristics of the specific language that is to be learned, although some of the cognitive skills that underlie foreign language reading acquisition appear to have a universal influence.
- Phonological processing seems to be more important for learning to read in foreign languages with alphabetic orthographies than in foreign languages with morpho-syllabic orthographies, whereas visual processing seems to be more important for learning to read in morphosyllabic orthographies, at least in the first stages of foreign language learning.

The presented research thus taught us that fluent word reading is characterised by a highly rapid translation of orthographic into phonological word representations. This indicates that orthography-phonology connections are fully automatized in fluent readers. However, the development of this automatisation process seems not to be completed yet at the end of elementary school. These findings thus challenge educational practice in which reading fluency is only taught explicitly until grade 4. Such practice relies on the implicit assumption that reading development has already been completed at the end of grade 4. The current research counters this assumption and suggests that the development of fluent reading skills continues far longer, at least until secondary education. Explicit training in word reading fluency may therefore be warranted even in the higher grades of primary education.

In addition, the research in the current thesis showed that emotional factors, specifically feelings of uncertainty, play a role in reading fluency, even at the single word level. Poor word reading fluency is generally attributed to poor phonological processing skills, especially in dyslexic readers. Hence, remedial programs for poor readers, in education as well as in specialised dyslexia institutions, are usually based on enhancing these phonological processing skills. Our research supports this focus on phonological processes, as impairments in phonological processing appeared to constitute the main factor underlying dyslexic children's poor word reading fluency. However, our research suggests that the effectively of such programs may be enhanced when emotional aspects of reading are addressed as well. This requires that emotional aspects of reading are considered an essential aspect of reading training instead of an unfortunate consequence that will automatically disappear with improved reading skills.

Finally, we learned from the presented research that learning to read in a foreign language occurs through different processes in different foreign languages. This qualifies the idea, held by scientists as well as practitioners, that being poor in one's native language generally results in poor performance in the second language as well. In line with this popular idea, findings do suggest that a poor reader of Dutch with poor phonological processing skills may be at risk for poor performance when learning to read in foreign alphabetic orthographies. However, this study also shows that if the lack of phonological skills is combined with adequate reasoning and visual processing skills, he or she may be successful in developing reading skills in morphosyllabic orthographies that use a visually complex script, like Chinese.

Summary

Summary

Even though the human brain is probably not equipped with a specialized reading area, most adults in western countries are able to recognize written words with great ease and speed. In fact, the ability to read fluently has become essential for successful participation in modern society. Despite the importance of fluent reading skills, most research thus far has focused on reading accuracy (Share, 2007). Reading accuracy is a highly important element of reading development in nontransparent orthographies such as English, where the relation between letters and the pronunciation of these letters is often unpredictable (compare the pronunciation of /o/ in 'rock', 'no', 'down', 'love' en 'lose'). However, in transparent languages such as Dutch, where relations between letters and speech sounds are more straightforward, reading accuracy is typically achieved rapidly by beginning readers (Seymour, Aro & Erskine, 2003), whereas fluency in reading takes much longer to develop (Vaessen & Blomert, 2010). Moreover, dysfluent reading constitutes the most persistent symptom of children with dyslexia (Blomert, 2011; Wimmer & Mayringer, 2002). This suggests that after accurate reading skills are established, an important phase of reading development concerns the fine tuning of reading skills into a rapid and efficient word recognition system. The studies in the current thesis aimed to improve our understanding of this phase in which reading fluency develops, both in typical readers and children with dyslexia. The studies specifically focused on the cognitive and affective mechanisms that underlie successful and failing reading fluency development.

The first two chapters focus on the formation of orthography-phonology connections, i.e. the connections between the written form (orthography) and spoken form (phonology) of words. Efficient integration of orthography and phonology during reading has been shown to constitute an essential component of reading fluency (Blau et al., 2009; 2010), and impairments in the timing of orthography-phonology integration have been assumed to underlie the dysfluency that characterizes dyslexic readers (Breznitz, 2002; 2006; Breznitz and Misra, 2003). However, the exact timing of orthography-phonology integration during reading in Dutch is thus far unknown, and it is unclear how this timing develops when children learn to become fluent readers. Therefore, in chapters two and three, the timing of orthographic and phonological activation during word reading was examined in skilled and developing Dutch readers at incremental levels of reading development.

The first study (chapter two) investigated how quickly skilled readers can activate orthographic codes during reading, and how quickly these orthographic codes are subsequently translated into phonological codes in order to access word meaning. To this end, a masked priming paradigm was used to study orthographic and phonological priming effects, since this paradigm allows investigation of the early stages of the reading process in which activation of orthography and phonology occurs. In typical Dutch words, orthography and phonology appeared to be so strongly interconnected that effects of orthography and phonology could not be separated. However, with the use of stimulus words that allowed better differentiation between orthography and phonology, it became clear that orthographic and phonological code activation follow distinct time courses. Orthography seemed to be accessed initially yet orthographic codes were quickly translated into phonological codes with

phonological influences dominating the remainder of the lexical access stage. A comparison to time courses previously reported for skilled readers of the nontansparent French orthography (Ferrand & Grainger, 1993), suggests that the translation of orthographic representations into phonological representations occurs slightly earlier in transparent than opaque orthographies.

The first study identified the timing of orthographic and phonological processing in readers who had fully integrated orthography-phonology associations. The second study (chapter 3) investigated how these orthography-phonology associations develop when children learn to become fluent readers. Therefore we used the same masked priming paradigm as in chapter 2 with children at incremental levels of reading development (grade 2, grade 6, grade 8). Even the youngest children in this study, who had received 1,5 year of reading instruction, seemed able to access orthographic representations during the first, not fully conscious, lexical access stage of the word recognition process. During reading development, orthographic codes became increasingly early accessible, which suggests increasing levels of automatisation. In contrast, phonological representations did not seem to be accessed during the early lexical access stage of word recognition in developing readers. This tentatively suggests that phonological processes are not yet automatized in 2nd to 6th grade readers, and that automatic phonological processing emerges later in development.

The third and fourth study did no longer focus on orthography-phonology integration, but on other processes that underlie reading fluency. The third study (chapter 4) examined the effects of phonological processing skills and feelings of uncertainty on word recognition fluency in children with dyslexia. The dyslexic children experienced impairments in visual word recognition, which appeared to primarily result from underlying phonological processing deficits. However, the impact of the phonological deficits seemed to be exacerbated by uncertainty. This suggests that the heightened levels of uncertainty that children with dyslexia experience are not only a consequence but also a cause of their word reading difficulties. The reading and emotional problems of dyslexic children therefore appear mutually reinforcing. The phonological processing deficits were also found to impair the children with dyslexia on auditory word recognition, specifically on speech-in-noise perception. However, uncertainty did not hamper dyslexic children during the recognition of auditory words. This suggests that the negative influence of emotional problems is specific to the task on which children with dyslexia have experienced repeated failure: reading.

In the fourth study (chapter 5), the focus shifted to the acquisition of reading fluency in a foreign language. This study investigated to what extent the influence of underlying language and cognitive skills is similar across foreign languages, or dependent on the language's orthographic transparency or writing system. To this end we studied children who were fluent readers of Dutch and were simultaneously learning to read in Spanish (a transparent alphabetic orthography), French (a deep alphabetic orthography) and Chinese (a morphosyllabic orthography). Some of the cognitive skills that underlay foreign language reading acquisition appeared to have a universal influence and to play a role in all three languages studied. However, the skills that most strongly affected foreign language reading acquisition depended on characteristics of the language concerned. That is, when native speakers of a language with a transparent alphabetic orthography (Dutch) learn to read in another transparent alphabetic orthography (Spanish), they seem to mainly adopt the reading skills that they already established in their native language to acquire knowledge about the new orthography. However, when the foreign orthography employs more complex letter-speech sound mappings (French), the letter-sound connections of the native language are insufficiently informative, and broader linguistic knowledge and reasoning skills need to be called upon to get a grip on the orthographic structure of the new language. When reading skills are acquired not in the familiar alphabetic writing system, but by means of visually complex characters (Chinese), visual and nonverbal skills become important to decode these characters and attach meaning to their visual forms.

Although speculative, these finding suggest that different patterns of cognitive skills may be related to successful reading acquisition in different foreign languages. For example, children with strong phonological skills seem likely to achieve high reading proficiency in foreign languages with alphabetic orthographies. Children with poor phonological skills and naming speed but adequate reasoning and visual skills, including many children with dyslexia, may expect greater academic success when learning a nonalphabetic orthography.

The joint results of the four studies in the current thesis have added new insights to our understanding of word reading fluency development, and have implications for both theories of reading and for reading education. These implications, as well as suggestions for further research are discussed in chapter 6.

Samenvatting

Samenvatting

Het menselijke brein is waarschijnlijk niet uitgerust met een gespecialiseerd leesgebied. Toch kunnen de meeste volwassenen in westerse landen geschreven woorden bijzonder snel herkennen, zonder dat dit veel inspanning vergt. Vloeiende leesvaardigheden zijn zelfs essentieel om succesvol te kunnen participeren in de moderne samenleving. Ondanks het belang van vloeiende leesvaardigheden, heeft het meeste onderzoek zich tot nu toe gericht op de nauwkeurigheid van het lezen (Share, 2007). Leesnauwkeurigheid is een belangrijk element van de leesontwikkeling in niet-transparante talen zoals het Engels, waarin de relatie tussen letters en de uitspraak van deze letters vaak onvoorspelbaar is (vergelijk de uitspraak van de /o/ in 'rock', 'no', 'down', 'love' en 'lose'). Echter, in transparante talen zoals het Nederlands, waarin de relaties tussen letters en uitspraak veel eenduidiger zijn, bereiken beginnende lezers al snel een hoge nauwkeurigheid (Seymour, Aro & Erskine, 2003) terwijl leesvloeiendheid veel trager ontwikkelt (Vaessen & Blomert, 2010). Bovendien vormen leesvloeiendheidsproblemen het meest hardnekkige symptoom van dyslexie (Blomert, 2011; Wimmer & Mayringer, 2002). Dit suggereert dat na het bereiken van leesnauwkeurigheid, een belangrijke fase in het leesproces bestaat uit het verfijnen van de leesvaardigheden tot een snel en efficiënt woordherkenningsysteem. De studies in dit proefschrift hadden als doel om ons begrip te vergroten van deze fase waarin leesvloeiendheid ontwikkelt, zowel bij gemiddelde lezers en kinderen met dyslexie. De studies richtten zich specifiek op de cognitieve en affectieve mechanismen die ten grondslag liggen aan succesvolle en stagnerende leesvloeiendheidsontwikkeling.

De eerste twee hoofdstukken zijn gericht op de vorming van orthografie-fonologie verbindingen, oftewel verbindingen tussen de geschreven vorm (orthografie) en klankvorm (fonologie) van woorden. Eerder onderzoek heeft namelijk aangetoond dat efficiënte integratie van orthografie en fonologie tijdens het lezen, een essentiële component vormt van leesvloeiendheid (Blau et al., 2009; 2010), en dat tekorten in de timing van orthografie-fonologie integratie ten grondslag liggen aan de leesvloeiendheidsproblemen die kenmerkend zijn voor dyslectische lezers (Breznitz, 2002; 2006; Breznitz & Misra, 2003). Echter, de precieze timing van orthografie-fonologie integratie tijdens het lezen in het Nederlands is onbekend, en het is bovendien onduidelijk hoe deze timing zich ontwikkelt wanneer kinderen leren om vloeiend te lezen. Daarom is in hoofdstuk twee en drie de timing van orthografische en fonologische activatie tijdens het woordlezen bestudeerd in Nederlandse vloeiende lezers en Nederlandse kinderen in verschillende fasen van de leesvloeiendheidsontwikkeling.

De eerste studie (hoofdstuk 2) onderzocht hoe snel vloeiende lezers orthografische informatie kunnen activeren tijdens het lezen, en hoe snel deze orthografische informatie vervolgens wordt omgezet in fonologische informatie om zo de betekenis van het betreffende woord te achterhalen. Daartoe werd een masked priming paradigma met orthografische en fonologische primes gebruikt, aangezien dit paradigma het mogelijk maakt de vroegste fase van het leesproces te bestuderen waarin orthografische en fonologische informatie geactiveerd wordt. In typische Nederlandse woorden bleken orthografie en fonologie zo sterk met elkaar verbonden te zijn dat orthografische en fonologische effecten niet onderscheiden konden worden. Echter, wanneer woorden werden geselecteerd waarbij orthografie en fonologie beter gescheiden konden worden, bleek dat orthografische en fonologische priming effecten verschillende tijdspaden vertoonden. Orthografie bleek eerst geactiveerd te worden, maar orthografische codes werden snel vertaald naar fonologische codes, en fonologische processen bleken het meest invloedrijk tijdens de rest van de vroege fase van het woordherkenningsproces waarin toegang tot de woordrepresentatie wordt verkregen. Een vergelijking tussen de gevonden tijdspaden in vloeiende Nederlandse lezers en eerder gerapporteerde tijdspaden in vloeiende lezers van het Franse (niet transparante) schrift (Ferrand & Grainger, 1993) liet zien dat de vertaling van orthografische representaties naar fonologische representaties mogelijk iets sneller verloopt in transparante dan in minder transparante orthografieën.

De eerste studie bracht de timing van orthografische en fonologische processen bij lezers met volledig geïntegreerde orthografie-fonologie verbindingen in kaart. In de tweede studie (hoofdstuk 3) werd onderzocht hoe die orthografie-fonologie verbindingen ontwikkelen wanneer kinderen vloeiend leren lezen. Daartoe werd hetzelfde masked priming paradigma als in hoofdstuk 2 gebruikt bij kinderen in verschillende fasen van de leesvloeiendheidsontwikkeling (groep 4, groep 6 en groep 8). Zelfs de jongste kinderen in deze studie, die 1,5 jaar leesonderwijs hadden gevolgd, bleken in staat om orthografische representaties op te roepen tijdens de eerste, nog niet volledig bewuste, fase van het woordherkenningsproces waarin toegang tot de woordrepresentatie wordt verkregen. Gedurende de leesontwikkeling konden de orthografische representaties steeds vroeger worden opgeroepen, wat duidt op een toenemende automatisering van orthografische processen. Fonologische representaties daarentegen, leken door geen van de groepen kinderen opgeroepen te kunnen worden tijdens deze vroege fase van het woordherkenningsproces. Dit suggereert dat fonologische processen wellicht nog niet geautomatiseerd zijn bij leerlingen in groep 4 t/m 8, en dat automatische fonologische verwerking pas later in de leesontwikkeling ontwikkelt.

De derde en vierde studie waren niet meer gericht op orthografie-fonologie verbindingen, maar op andere processen die ten grondslag liggen aan leesvloeiendheid. De derde studie (hoofdstuk 4) onderzocht de invloed van fonologische verwerkingsvaardigheden en gevoelens van onzekerheid op woordherkenningsvloeiendheid bij kinderen met dyslexie. Hierbij werd gebruik gemaakt van het diffusiemodel. De dyslectische kinderen vertoonden tekorten in hun visuele woordherkenningsvaardigheden. Deze tekorten bleken primair veroorzaakt te worden door beperkingen in de onderliggende fonologische verwerkingsprocessen. Echter, de impact van deze fonologische beperkingen werd versterkt door onzekerheid. Dit suggereert dat de verhoogde gevoelens van onzekerheid die kinderen met dyslexie ervaren, niet alleen het gevolg, maar ook een oorzaak zijn van hun leesproblemen. De lees- en emotionele problemen van kinderen met dyslexie lijken elkaar dus wederzijds te versterken. De fonologische verwerkingsproblemen van de kinderen met dyslexie bleken ook een belemmerende invloed te hebben op hun auditieve woordherkenningsvaardigheden, met name bij het herkennen van spraak in ruis. De emotionele problemen bleken echter uitsluitend te spelen bij visuele woordherkenning, en bleken geen belemmerende rol te spelen bij het auditief herkennen van woorden. Dit wijst er op dat de negatieve invloed van emotionele problemen niet algemeen is, maar specifiek van invloed is bij de taak waarop kinderen met dyslexie herhaaldelijke faalervaringen hebben opgedaan: lezen.

In de vierde studie (hoofdstuk 5), werd de focus verlegd naar de ontwikkeling van leesvloeiendheid in een vreemde taal. Deze studie onderzocht of de invloed van onderliggende taal- en cognitieve vaardigheden op de ontwikkeling van leesvloeiendheid gelijk is voor verschillende vreemde talen, of afhankelijk is van de orthografische transparantie of het schrijfsysteem van de betreffende taal. Hiertoe bestudeerden wij kinderen die vloeiend konden lezen in het Nederlands en die gelijktijdig leerden lezen in het Spaans (oppervlakkige alfabetische orthografie), Frans (diepe alfabetische orthografie) en Chinees (morphosyllabische orthografie). Sommige cognitieve vaardigheden die ten grondslag liggen aan de ontwikkeling van leesvloeiendheid in een vreemde taal bleken een universele invloed te hebben, en een rol te spelen bij elk van de drie bestudeerde talen. Echter, de vaardigheden die de grootste invloed hadden waren taalspecifiek. Namelijk, wanneer vloeiende lezers van een taal met een transparante alfabetische orthografie (Nederlands), leren lezen in een andere transparante alfabetische orthografie (Spaans), maken zij voornamelijk gebruik van de leesvaardigheden die zij al in hun moedertaal hebben ontwikkeld om kennis te vergaren over de nieuwe orthografie. Echter, wanneer de vreemde taal minder transparante en dus meer complexe letter-klank verbindingen bevat (Frans), zijn de letter-klank verbindingen die worden beheerst in de moedertaal niet langer voldoende informatief. Bredere taalvaardigheden en redeneervaardigheden moeten dan worden ingezet om grip te krijgen op de orthografische structuur van de nieuwe orthografie. Wanneer leesvaardigheden worden ontwikkeld in een vreemde taal waarin geen gebruik wordt gemaakt van het bekende alfabetische schrift, maar van visueel complexe karakters (Chinees), zijn visuele en nonverbale vaardigheden van belang om deze karakters van elkaar te onderscheiden en er betekenis aan te verlenen.

Deze bevindingen suggereren, weliswaar speculatief, dat verschillende patronen van cognitieve vaardigheden gerelateerd zijn aan succesvolle leesontwikkeling in verschillende vreemde talen. Zo lijken kinderen met sterke fonologische vaardigheden beter toegerust voor het ontwikkelen van goede leesvaardigheden in talen met alfabetische orthografieën. Kinderen met zwakke fonologische vaardigheden en een lage benoemsnelheid maar adequate redeneer en visuele vaardigheden, waaronder veel kinderen met dyslexie, ervaren daarentegen mogelijk meer succes wanneer zij leren lezen in een niet alfabetische orthografie.

De gecombineerde resultaten van de vier studies in het huidige proefschrift hebben nieuwe inzichten opgeleverd met betrekking tot de ontwikkeling van woordleesvloeiendheid. Bovendien hebben de resultaten implicaties voor zowel theorieën over lezen als voor het leesonderwijs. Deze implicaties en ook suggesties voor vervolgonderzoek zijn besproken in hoofdstuk 6.

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Supplemental material

Supplemental material

Table S1
Stimulus set of Study 1 in chapter 2 and chapter 3

Word Target	Phonological prime	Orthographic prime	Control prime	Foil Target	Phonological prime	Orthographic prime	Control prime
zout	zaut	zeut	peik	rouf	rauf	reuf	pied
stout	staut	steut	breil	knouf	knauf	kneuf	vreip
vrucht	vrugt	vrelt	swink	zwacht	zwagt	zwant	prelf
lijn	lein	luin	meup	nijf	neif	nuif	zaul
auto	outo	euto	ieke	auzu	ouzu	euzu	ielo
hemd	hemt	hems	gals	jemd	jemt	jems	girk
darm	darrem	darsom	jolkep	sarm	sarrem	sarfom	viltog
tijger	teiger	tuiger	pouvus	lijger	leiger	luiger	zaumon
mouw	mauw	muuw	keip	souw	sauw	seuw	jieg
zalm	zallem	zalgim	vepris	valm	vallem	valsim	perfok
konijn	konein	konuin	gelaus	polijn	polein	poluin	kaveus
lekker	lekkur	lekkar	tammon	sekker	sekkur	sekkar	tillof
taxi	taksi	talgi	perko	goxi	goksi	gofti	purfa
actie	aksie	amdie	omdou	octie	oksie	onfie	aslau
radijs	radeis	raduis	voteun	pavijs	paveis	pavuis	zereul
breed	breet	breef	kwaaf	steed	steet	stees	kruun
clown	klaun	sleun	greur	cloem	kloem	gloem	spaaf
zestig	sestig	kestig	mondap	zoster	soster	roster	minkal
smid	smit	smin	vrol	vlid	vlit	vlim	swal
zwijn	zwein	zwuin	craus	gnijn	gnein	gnuin	spoer
bouw	bauw	beuw	keem	doup	daup	deup	liek
afval	affal	afral	etrot	ufvon	uffon	ufkon	eskap
circus	sirkus	wirpus	wontam	circam	sirkam	pirzam	lonpel
boog	booch	bookt	reeft	joog	jooch	joosp	veent
half	hallef	haldif	gertop	valf	vallef	valdif	gonsuk
scherp	sgerp	slerp	klomt	schilk	sgilk	smilk	brend
geld	gelt	gelf	zarm	neld	nelt	nelg	romf
recht	regt	relt	ponf	mecht	megt	ment	lors
hotel	hootel	houtel	puivak	lotel	lootel	loutel	hauzam
kerk	kerrek	kerpok	vultap	herk	herrek	herzik	pinvol
nacht	nagt	nakt	heps	hocht	hogt	homt	pilf
anker	angker	ansker	uscham	onker	ongker	olpker	amflam
brand	brant	brank	slops	fland	flant	flanp	krosp
club	klup	flum	swar	creb	krep	frel	flis
recept	resept	refept	jovank	bacipt	basipt	bafipt	kelens
cirkel	sirkel	birkel	gostaf	cerpas	serpas	gerpas	honvig
wolk	wollek	woltik	samvun	julk	jullek	julzak	zormig
worm	worrem	worsam	pelvek	morm	morrem	morgam	gelkin
vriend	vrient	vriens	klaums	spiend	spient	spienf	draalm
pauze	pouze	peuze	wijma	gaume	goume	guume	looga
pauw	pouw	puuw	teim	faul	foul	feul	hoeg
liter	lieter	lijter	woutos	gimel	giemel	gijmel	pouvor
azijn	azein	azuin	opeul	avijs	aveis	avuis	upoel
vijand	veiant	vuiank	leuork	bijond	beiont	beionk	gaualf
gebouw	gebauw	gebeuw	kazaar	bevouw	bevauw	beveuw	malaaf
extra	ekstra	elftra	uschlo	axtro	akstro	alftro	echplu
kiwi	kiewie	kijwij	boerau	ripi	riepie	rijpij	veunoe
veter	veeter	veuter	kauzap	geter	getur	getar	zalis
chips	sjips	krips	glerk	shonk	sjonk	kronk	vrimp
show	sjow	plow	grik	shan	sjan	klan	prig
score	skore	slore	fluka	scame	skame	stame	prilo
traag	traach	traalf	fleenk	spaag	spaach	spaalf	kruuft
vork	vorrek	vortik	salbam	gork	gorrek	gornak	pilmas
koord	koort	koorm	vuuns	heerd	heert	heerm	luusk
vlag	vlach	vlans	prunk	smag	smach	smank	klirf
hark	harrek	harpok	pelmes	gerk	gerrek	gervik	posnal

Table S1 (continued)
Stimulus set of Study 1 in chapter 2 and chapter 3

Word Target	Phonological prime	Orthographic prime	Control prime	Foil Target	Phonological prime	Orthographic prime	Control prime
vonk	vongk	vonsk	parft	nank	nangk	nansk	rilft
bank	bangk	bansk	vorgt	fink	fingk	finsk	gocht
stank	stangk	stansk	prelch	glonk	glongk	glonsk	bremsp
drank	drangk	dransk	plirft	knank	knangk	knansk	frecht
geluk	guluk	galuk	mazon	bemuk	bumuk	bamuk	rivan
sorry	sorrie	sorrau	bullau	hirry	hirrie	hirrau	mossoe
jarig	jareg	jarog	pepen	nurig	nuurig	nuirig	poelem
lelijk	leluk	lelok	rovan	belijk	beluk	belok	rusof
echo	eggo	ello	unna	ocha	ogga	ossa	eppi
nuttig	nutteg	nuttag	loppes	jottig	jotteg	jottag	kalles
chaos	gaos	baos	duek	cheof	geof	leof	kual
titel	tietel	tijtel	paukon	hisel	hiesel	hijsel	lauvor
baby	beebie	boebeu	kuiloe	hely	helie	helau	tavou
water	watur	wator	solum	gater	gatur	gatir	zovin
bakker	bakkur	bakkir	nommil	hasser	hassur	hassor	pollig
lijst	leist	luist	koenf	wijnt	weint	wuint	boelk
veilig	veileg	veilag	pautak	naulig	nauleg	naulog	voesem
peper	peeper	peuper	kaulan	tuper	tuuper	tuiper	laanom
foto	footoo	foutoe	piekee	sato	saatoo	sautoe	muilei
zwaard	zwaart	zwaark	stuugs	blaard	blaart	blaark	sguunf
schil	sgil	snil	prod	schak	sgak	spak	trot
gelijk	geleik	geluik	pavoos	bezijk	bezeik	bezuik	paraul
adres	aadres	audres	ousgom	adros	aadros	audros	eilkim
blond	blont	blons	stegs	sjond	sjont	sjonp	vlamk
dorp	dorrep	dorlip	kesten	wurp	wurrep	wurlap	pilnos
bezem	beezem	beuzem	kauras	jalen	jaalen	jaulen	nookis
koud	kaut	keum	peif	doud	dout	doul	ziem
goud	gaut	geuf	peek	noud	naud	neud	jeis
strijd	streit	struil	chlauf	splijd	spleit	spluim	chrauf
file	fiele	fijle	pauta	dile	diele	dijle	houma
succes	sukses	sulpes	halzaf	mocces	mokses	morfes	balzik
geluid	geluit	geluin	bazoor	bemuid	bemuit	bemuig	ravaus

Table S2
Lexical characteristics of the targets and primes in each of the four target conditions of study 1 in chapter 2 and chapter 3

	Word Targets	Nonword Targets
Target characteristics		
Celex frequency	60,08 (78,07)	--
Subtlex frequency	67,45 (129,53)	--
Bigram frequency	29717,98 (20525,51)	27765,93 (19637,01)
Nsize	3,99 (3,75)	3,44 (3,46)
Lettersize	4,90 (0,78)	4,86 (0,78)
N mean frequency	1572,54 (3798,2)	965,54 (1809,24)
Frequency HFN	5318,01 (12924,92)	3574,93 (7374,07)
Prime characteristics		
FP Bigram frequency	32557,00 (21059,34)	30648,01 (19960,54)
OP Bigram frequency	29864,74 (16954,81)	27444,90 (17018,35)
CP Bigram frequency	25687,66 (15276,14)	25518,48 (14460,95)
FP Nsize	2,11 (2,49)	1,52 (2,39)
OP Nsize	2,24 (2,69)	1,52 (2,52)
CP Nsize	1,89 (3,14)	1,80 (2,96)
FP Lettersize	5,31 (0,77)	5,30 (0,79)
OP Lettersize	5,31 (0,77)	5,30 (0,79)
CP Lettersize	5,31 (0,77)	5,30 (0,79)
FP N mean frequency	970,37 (2156,24)	508,73 (1991,58)
OP N mean frequency	1100,50 (2491,87)	320,56 (836,55)
CP N mean frequency	194,67 (434,83)	404,65 (1688,36)
FP frequency HFN	2057,74 (3699,91)	1144,01 (4000,17)
OP frequency HFN	2252,01 (4907,41)	1458,20 (6554,44)
CP frequency HFN	797,06 (2606,48)	1897,78 (10646,08)

Note. Nsize = number of neighbours, N mean frequency = mean frequency of neighbours, N highest frequency = frequency of highest frequent neighbor. All values, except for the Subtlex frequency, are based on the Celex database. Frequency is expressed in frequency per million.

Table S3
Stimulus set of the PD small condition of study 2 in chapter 2 and chapter 3

Word Target	Phonological prime	Orthographic prime	Control prime	Foil Target	Phonological prime	Orthographic prime	Control prime
azijn	azein	azuin	opeul	orijn	orein	oruin	ageus
gebod	gebot	gebor	humas	gelad	gelat	gelar	bikom
schim	sgim	sfim	wran	schek	sgek	smek	blam
smaad	smaat	smaar	vroel	wraad	wraat	wraan	bluuk
milieu	miljeu	milkeu	parnoo	galieu	galjeu	galkeu	borkoo
voogd	voogt	voogs	meenk	roegd	roegt	roegs	buils
beleg	belech	belerk	karomt	geleg	gelech	gelerk	divast
zwijn	zwein	zwuin	craus	snijn	snein	snuin	droep
afval	affal	afral	etrot	ufvan	uffan	ufban	erdos
lobby	lobbie	lobbau	hannau	mobby	mobbie	mobbeu	fallau
specht	spegt	spemt	brank	smicht	smigt	smipt	fralp
steeg	steech	steeks	bruink	kweeg	kweech	kweeft	broost
rugby	rugbie	rugboe	mondoe	kurby	kurbie	kurbau	galmoe
dictee	diktee	dirtee	porfau	voctee	voktee	vortee	gaspui
bezem	beezem	beuzem	kauras	hezem	heezem	heuzem	gaupal
loyaal	lojaal	losaal	pikeen	koyaal	kojaal	konaal	gemuun
score	skore	slore	fluta	scave	skave	spave	gludo
kwaad	kwaat	kwaag	broup	sjaad	sjaat	sjaaf	gruum
royaal	rojaal	ronaal	tumien	noyaar	nojaar	nogaar	gurees
toupet	toepet	toopet	jaakil	kouzet	kauzet	keuzet	haapil
zijde	zeide	zuide	hauna	wijpe	weipe	wuipe	launa
sauna	souna	suuna	reido	taura	toura	tuura	heizo
tyfus	tiefus	toefus	koerig	rifus	riefus	rijfus	hoeleg
casus	kasus	vasus	movel	cabus	kabus	labus	homon
golf	golph	golst	renkt	sulf	sulph	sulch	horkt
enzym	enziem	enzoem	irvuik	orzym	orziem	orzoem	inluik
konijn	konein	konuin	gelaus	gomijn	gomein	gomuin	japeus
badjas	batjas	bakjas	zinpok	kadzas	katzas	karzas	jepmen
radijs	radeis	raduis	voteun	lavijs	laveis	lavuis	jogeum
retour	retoer	retoor	kinaam	ravour	ravoer	ravoor	kileen
vlug	vluch	vlust	stesp	vrag	vrach	vralm	blong
jurist	yurist	gurist	panelf	jupest	yupest	hupest	ladork
bewijs	beweis	bewuis	gazuul	kawijs	kaweis	kawuis	lumoef
pauze	pouze	peuze	wijmo	hauve	houve	heuve	lijdo
virus	vierus	vijrus	moekel	girus	gierus	gijrus	loeden
hemd	hemt	hemf	gals	nend	nent	nenk	loks
portie	porsie	porvie	kulmau	torcie	torkie	torvie	malbau
gebouw	gebauw	gebeuw	kazaar	bekouw	bekauw	bekeuw	mizaal
nylon	neilon	naulon	wuipak	nijkon	neikon	nuikon	peuzag
zwaard	zwaart	zwaark	stuugs	skaard	skaart	skaarp	plienf
fauna	founa	fuuna	goele	haula	houla	huula	poete
bidon	biedon	bijdon	waakus	bazon	baazon	bauzon	luidel
klucht	klugt	klurt	vramp	stucht	stugt	stumt	prilf
pipet	piepet	pijpet	loumas	kivet	kievet	kijvet	raulom
lijst	leist	loist	koenk	tijkt	teikt	tuikt	feens
tanker	tenker	tunker	pimsul	tauser	touser	tuuser	loovik
saus	sous	seus	vein	mauf	mouf	meuf	seig
wrok	vrok	crok	sneg	wrop	vrop	grop	slif
fjord	fjort	fjork	snilk	klord	klort	klorm	smans
buurt	buurd	buurk	jijns	yeurt	yeurd	yeurk	lijsp
locus	lokus	lomus	ramin	gacus	gakus	gamus	tovem
tuig	tuich	tuilf	keenp	suig	suich	suift	feekt
sofa	soofa	soefa	lieme	loja	looja	loeja	viege
route	roete	roote	wijla	doupe	daupe	deupe	vijla
trauma	trouma	truuma	kleipe	spauma	spouma	spuuma	vreige
show	sjow	skow	grik	shak	sjak	scak	vrul

Table S3 (continued)
Stimulus set of the PD small condition of study 2 in chapter 2 and chapter 3

Word Target	Phonological prime	Orthographic prime	Control prime	Foil Target	Phonological prime	Orthographic prime	Control prime
decor	dekor	denor	jamif	bacor	bakor	bator	wiven
burcht	burst	burkt	kalps	warcht	wargt	warst	zunks
brug	bruch	brund	stesk	vrog	vroch	vrond	scenp
flat	flet	flot	krun	flaut	flout	fleut	zweip

Table S4
Stimulus set of the PD large condition of study 2 in chapter 2 and chapter 3

Word Target	Phonological prime	Orthographic prime	Control prime	Foil Target	Phonological prime	Orthographic prime	Control prime
iglo	iegloo	ijglou	auksee	yflo	iefloo	euflou	aakzei
echo	eggoo	ellou	annui	ucho	uggoo	ullou	arrie
eiland	ijlant	ielans	oupors	eigond	ijgont	iegons	auvalk
douche	doesj	doonk	maark	douga	daucha	duuspa	beefki
coach	kootsj	moenkt	reilft	culph	kulf	muld	bogd
schild	sgilt	spilk	brump	schund	sgunt	slunk	wrelp
diner	dienee	dijneu	soutau	difé	diefee	dijfeu	goumoo
vijand	veiant	vuiank	leuork	voyand	vojant	vorank	bulirk
luxe	luukse	luinde	bijfza	meixe	mijkse	miende	paulvo
exact	eksakt	erpalt	ongisp	axict	aksikt	alvirt	erpons
zout	zaud	zeuf	peig	paut	poud	peuf	rool
cowboy	kauboi	leibou	meedeu	coubod	kaubot	heubol	fijgas
clown	klaun	sleun	greur	croud	kraut	preum	flaas
hout	haud	heuf	seim	dout	daud	deup	pieg
quote	kwoot	grout	knaaf	quint	kwind	scink	sperg
cactus	kaktus	lamtus	perfol	cocpus	kokpus	rofpus	gimbal
circus	sirkus	mirbus	lemvan	cercas	serkas	vermas	gitvol
design	dizijn	davien	hopuur	dysaun	disoun	doseun	gomool
cola	koola	moela	veuze	copu	koopu	roepu	haame
inhoud	inhaut	inhuuk	arwees	ankoud	ankaut	ankuug	irpeel
pizza	pietsa	pijlma	foerke	piga	piecha	pijnsa	roende
twijg	tweich	twuils	spoerk	vrijg	vreich	vreups	sloenp
jeep	djiep	kjoep	bruil	geip	chijp	vriep	klaam
chips	sjips	vrips	glerk	shind	sjint	skinf	bralk
baby	beebie	boebeu	kuiloe	taby	taabie	tauboe	reivee
toilet	twalet	trulet	skunas	qualet	kwalet	spalet	vrizon
beige	bezje	berle	mupso	veige	vijche	viente	noospa
accent	aksent	ampent	olmirp	exant	eksant	erbant	omvilf
etui	eetwie	eitsij	aalkoo	agei	aachij	austie	ooskou
email	iemeel	oemoul	ousuur	eimaul	ijmoul	iemuul	oovoos
coupé	koepee	roopei	dijmai	couré	koeree	poorei	paamij
kilo	kieloo	kijlou	peunau	vizo	viezoo	vijzou	paudee
racket	rekket	ronket	bossin	raucet	rouket	ruulet	foolin
hockey	hokkie	holkoe	pallui	nackey	nakkie	nalkoe	durmui
schub	sgup	snur	vlin	schac	sgak	smab	brif
jeugd	yeucht	leunks	voorks	jeegd	yeecht	heenks	puinks
coupon	koepon	doopon	reimil	cauves	kouves	beuves	roonig
panty	pentie	pontoe	lorbou	lauty	loutie	luutoe	reipoe
jury	sjurie	kjuree	spodoe	shory	sjorie	sloree	knazau
geisha	gijsja	giespa	vounko	peisho	pijsjo	pieslo	vaurza
cognac	konjak	polman	jispel	caggem	kachem	parvem	silbor
broche	brosj	brolf	fland	vroche	wrogge	kroppe	skunta
tissue	tisjoe	tispee	borvaa	tiggei	tichij	timpie	lampoo
wrak	vrac	prad	slen	wric	vrik	grin	spaf
jeans	djiens	pjoens	gruift	quans	kwans	vrans	blemt
club	klup	vlun	dwar	crub	krup	vrus	stig
circa	sirkaa	wirmau	peldou	cirpo	sirpoo	dirpou	talkau
cacao	kaakau	raudaa	peinee	caco	kaako	maulo	tuive
woud	waut	weum	bijg	noud	naut	neuf	peif
actie	aksie	amdie	omdou	octij	oktei	ontui	ufbau
jazz	djez	sjoz	frup	jaud	jout	jeun	keif
schuld	sgult	spulm	knorp	schald	sgalt	smalk	promf
schijf	sgeif	spuif	draap	schijl	sgeil	skuil	vrauk
truc	truuk	truig	smeif	trouc	trauk	treus	speif
quiz	kwis	blir	plen	quak	kwac	skap	vrip
cijfer	seifer	huifer	doupan	cijmor	seimor	buimor	waugan

Table S4 (continued)
Stimulus set of the PD large condition of study 2 in chapter 2 and chapter 3

Word Target	Phonological prime	Orthographic prime	Control prime	Foil Target	Phonological prime	Orthographic prime	Control prime
yoga	jooga	bouga	keite	yago	jaago	haugo	wijdu
foyer	fojee	fozeu	manui	doya	dojaa	domau	winei
schijn	sgein	stuin	flaak	schijp	sgeip	snuip	vreel
fiche	fiesje	fijlke	toumpa	figa	fiecha	fijnta	wuurto

Table S5
Lexical characteristics of the targets and primes in each of the four target conditions of study 2 in chapter 2 and chapter 3

	Word Targets with Small Phonological contrast	Word Targets with Large Phonological contrast	Nonword Targets with Small Phonological contrast	Nonword Targets with Large Phonological contrast
Target characteristics				
Celex frequency	20,63 (29,80)	19,15 (24,83)	--	--
Subtlex frequency	19,73 (35,83)	19,07 (32,42)	--	--
Bigram frequency	23193,50 (14679,98)	20416,70 (15261,46)	22079,88 (11906,08)	18950,86 (12194,45)
Nsize	1,69 (1,70)	1,69 (2,71)	1,44 (1,67)	1,49 (2,08)
Lettersize	5,15 (0,71)	5,06 (0,86)	5,18 (0,69)	5,00 (0,83)
N mean frequency	370,92 (754,58)	710,14 (2706,18)	311,60 (972,63)	363,48 (794,65)
Frequency HFN	744,89 (1570,82)	914,46 (2822,45)	597,47 (1933,55)	675,51 (1324,01)
Prime characteristics				
FP Bigram frequency	29747,46 (19707,06)	26905,52 (17714,85)	27289,84 (13882,68)	26067,63 (14164,92)
OP Bigram frequency	26597,11 (15957,54)	28369,56 (15840,80)	24610,60 (10539,05)	26484,56 (17383,03)
CP Bigram frequency	28843,46 (16493,40)	27106,65 (13171,24)	27996,40 (14923,23)	26784,83 (14030,48)
FP Nsize	1,61 (1,68)	0,83 (1,29)	1,21 (1,74)	1,15 (2,12)
OP Nsize	1,74 (2,07)	0,94 (1,43)	1,23 (2,20)	1,14 (1,92)
CP Nsize	1,78 (2,79)	0,94 (1,60)	1,32 (2,05)	1,19 (2,62)
FP Lettersize	5,35 (0,68)	5,44 (0,72)	5,37 (0,65)	5,44 (0,75)
OP Lettersize	5,35 (0,68)	5,46 (0,72)	5,37 (0,65)	5,44 (0,75)
CP Lettersize	5,35 (0,68)	5,46 (0,72)	5,37 (0,65)	5,44 (0,75)
FP N mean frequency	569,95 (1074,01)	701,67 (2612,04)	205,54 (520,65)	170,39 (481,72)
OP N mean frequency	493,74 (1074,04)	362,26 (1359,94)	168,12 (684,15)	191,46 (418,49)
CP N mean frequency	461,48 (1611,39)	808,10 (4469,24)	226,45 (483,05)	190,47 (471,59)
FP frequency HFN	1251,56 (3152,32)	1805,09 (7610,06)	521,44 (1829,12)	557,44 (1785,10)
OP frequency HFN	1214,98 (4050,54)	964,48 (4679,96)	495,77 (2112,69)	639,95 (1535,61)
CP frequency HFN	1084,28 (3404,29)	1643,06 (8968,13)	633,67 (1944,85)	698,47 (1997,62)

Note. Nsize = number of neighbours, N mean frequency = mean frequency of neighbours, N highest frequency = frequency of highest frequent neighbor. All values, except for the Subtlex frequency, are based on the Celex database. Frequency is expressed in frequency per million.

Table S6

Correlations among the native language and cognitive skills in chapter 5

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Dutch word reading	-																	
2. Dutch pseudoword reading	.75*	-																
3. Verbal IQ	.20*	.07	-															
4. Dutch vocabulary	.16*	.03	.37*	-														
5. Verbal reasoning	.14	.07	.51*	.45*	-													
6. Nonverbal IQ	.04	-.02	.17*	.25*	.22*	-												
7. Math abilities	.07	.10	.07	.24*	.18*	.53*	-											
8. Spatial reasoning	-.24*	-.24*	.17*	.12	.08	.39*	.23*	-										
9. Deletion 1 phoneme	.37*	.35*	.03	.14	.11	.03	.04	.03	-									
10. Deletion 2 phonemes	.31*	.34*	.07	.06	.10	.02	-.02	-.08	.46*	-								
11. RAN letters	.48*	.42*	-.18*	-.12	-.03	-.11	-.05	-.19*	.22*	.17*	-							
12. RAN digits	.53*	.46*	-.18*	-.16*	-.03	-.03	-.03	-.29*	.25*	.16*	.75*	-						
13. RAN colors	.42*	.33*	-.07	-.02	.07	-.03	.04	-.09	.24*	.24*	.46*	.49*	-					
14. RAN pictures	.42*	.33*	.00	.04	.13	.06	.03	-.02	.26*	.17*	.38*	.42*	.56*	-				
15. Coding	.22*	.19*	-.03	.01	.19*	.15	.15*	-.01	.04	.04	.27*	.26*	.27*	.29*	-			
16. Symbol search	.12	.07	.07	-.06	.15*	.15	.10	.13	.05	.03	.26*	.15*	.21*	.21*	.50*	-		
17. Digit span forward	.13	.15	-.09	.09	.02	.02	.02	-.09	.14	.17*	.12	.08	.08	.20*	-.03	-.09	-	
18. Digit span backward	.17*	.18*	-.03	.09	.19*	.08	.09	-.04	.11	.20*	.14	.13	.17	.32*	.16*	.12	.31*	-

Note. * $p < .05$

Table S7
Model estimated correlations among the native language and cognitive skills in chapter 5

	1	2	3	4	5	6	7	8
1. Dutch literacy skills	-							
2. Verbal intelligence	.216*	-						
3. Nonverbal intelligence	.040	.390**	-					
4. Phonological awareness	.581**	.174	.039	-				
5. Alphanumeric RAN	.657**	-.185*	-.100	.331**	-			
6. Nonalphanumeric RAN	.596**	.072	.072	.442**	.686**	-		
7. Visual processing speed	.270**	.120	.217*	.085	.402**	.457**	-	
8. Verbal memory	.259**	.152	.158	.353**	.188	.381**	.112	-

Note. * $p < .05$. ** $p < .01$.

About the author

About the author

Maaike Zeguers was born on september 6, 1982 in Hoorn. After obtaining a gymnasium degree at Martinuscollege in Grootebroek, she took part in an exchange student program. She studied for one year at Orange coast college in Costa Mesa, California (USA), with a master in Dance and a minor in Psychology. Upon her return in the Netherlands, she moved to Leeuwarden to study International hospitality management. She followed a three year fast track program. During the last year of this program, Maaike moved to Amsterdam to complete a management internship at Meeting Masters. In 2004 she obtained a Bachelor of Business Administration in International hospitality management. This same year she started studying Psychology at the University of Amsterdam (UvA). She obtained her Bachelor degree in 2008. In order to gain more insight in the field of education, she combined a master in Clinical developmental psychology , with a specialization in School Psychology and a master in Pedagogical sciences.

In 2009, Maaike obtained a master degree in both Psychology (cum laude), including School Psychology, and also in Pedagogical sciences. Subsequently, she started working as a PhD student at the department of Developmental Psychology of the UvA under supervision of dr. Patrick Snellings and professor Maurits van der Molen. Soon after startingthe PhD project, it was converted into a scientist-practitioner project. From 2010 onwards, Maaike combined her PhD work with a clinical job as an educational advisor at Onderwijs Advies in Leiden. In 2010 and 2011 she also followed the post master program Schoolpsychology at the RINO, Amsterdam. By completing this program she became a registered child psychologist (Registerpsycholoog NIP Kind & Jeugd, 2012) and educationalist (NVO Orthopedagoog generalist, 2015).

Currently, Maaike is employed as an assistant professor in Schoolpsychology at the department of Developmental Psychology of the UvA and she is one of the researchers in the Rudolf Berlin Center, the university center in the field of learning disabilities. In addition, she works as head clinician (hoofdbehandelaar) at the IWAL, an institute for learning disabilities. Maaike is a member of the NIP section of school psychologists. She has been a member of the organizing committee of the National School Psychology conference in 2015 and 2017. In 2016 she was on the scientific board of the organizing committee of the conference of the international school psychology association (ISPA). In 2013 Maaike completed the course on crisis intervention in schools. Since then, she is a member of the Dutch crisis intervention network. Since 2016, she teaches a postmaster course on dyslexia at the Rino.

List of publications

List of publications

International publications

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