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Jarkko Hautala

Visual Word Recognition in Fluent and Dysfluent Readers in the Transparent Finnish Orthography

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ABSTRACT

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The dual-route model of visual word recognition consists of a serial letter processor used for reading unfamiliar words, and a whole-word procedure capable of reading novel and irregularly spelled words. Dyslexics are thought to rely mainly on the serial reading procedure. Due to its transparent orthography, Finnish can be read solely by the serial procedure. This thesis studies what the relevant reading units in Finnish are including letters, syllables and words both in fluent and dysfluent readers. The first study, which explored eye movements during repeated reading of pseudo/words, indicated that dysfluently reading children relied strongly on the serial reading processor whereas the typical reading adult showed evidence for more holistic processing. Second, a study with second grade children added that dysfluent readers are deficient in phonemic assembly and more impaired when required to recognize the words, in which case they also assembled the phonemes into syllables. The third study demonstrated the existence of relatively independent systems for eye movement guidance and word recognition for the first time in natural reading. The number of letters affected fixation durations, whereas the words' spatial width determined landing positions in words and the probability of skipping a word. The fourth study examined if word recognition is serial and thus if words with a unique beginnings are responded to faster than words with non-unique beginnings. In line with the dual-route model, a unique initial syllable was beneficial in pseudoword recognition but not in word recognition. Dysfluent readers showed slower word recognition and a larger effect of the unique initial syllable of a pseudoword. To conclude, although word recognition in the transparent Finnish orthography may contain the rapid coding of a word's structure, this process is unlikely to be serial in nature, which is clearly the case when reading novel words. For dysfluent readers, serial decoding still seems to be the prevalent reading strategy in the fifth grade, but not in young adulthood. The results also suggest that problems in decoding interfere with attaining word meaning, in which syllabic decoding may be a helpful strategy.

Keywords: visual word recognition, developmental dyslexia, eye movements

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CONTENTS

1 GENERAL INTRODUCTION

Reading is an important basic skill for living in modern society. It is an effortless and automatic skill for most of us, yet approximately 6-17% of us are considered to have at least mild problems in reading (Fletcher, Lyon, Fuchs, & Barnes, 2007; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Puolakanaho, Ahonen, Aro et al., 2007). Cognitively, reading is a relatively specific and well-understood action and the reading disability, dyslexia, is probably the most specific among the learning disabilities (Fletcher et al, 2007), suiting experimental research well. Indeed, major advances in understanding cognitive deficits in dyslexia have been achieved, as reviewed by Vellutino et al. (2004), Rayner, Foorman, Perfetti et al. (2001), Fletcher et al. (2007), and Blomert (2011). Although the mainstream view is that dyslexia is a linguistic deficit, more specifically a deficit in phonological processing (Ramus, 2003) or in connectivity between orthographic and phonological representations (Wimmer & Schurz, 2010; Blomert, 2011), alternative views stress the importance of deficient visual and/or attentional processes in dyslexia (Bosse, Tainturier, & Valdois, 2007; Vidyasagar & Pammer, 2010) and the importance of these processes also in fluent reading (Pelli, Tillman, Freeman et al., 2007).

Alphabetic writing systems are symbol systems for representing spoken languages. Thus, the core of reading is the conversion of written to spoken language, which in fluent adult reading essentially happens at the level of words (Rayner et al., 2001; Coltheart, Rastle, Perry et al., 2001; Perry, Ziegler & Zorzi, 2007a). However, each language and writing system is unique and potentially read differently. Specifically, the level of systematicity in mapping between written and spoken language has been found to have profound influences on reading (Katz & Frost, 1992; Lukatela, Popadic, Ognjenovic & Turvey, 1980; Lukatela, Turvey, Feldman, Carello, & Katz, 1989) and particularly on reading development (Aro & Wimmer, 2003; Seymour, Aro & Erskine, 2003). Most of the prevalent models of word recognition (Coltheart et al., 2001; Seidenberg & McClelland, 1989; Perry et al., 2007a) have been developed in English, which has a rather complex relationship between the written and spoken languages. For reading irregularly spelled words, unique orthographic memory representations seem necessary, whereas regularly spelled words can be read by grapheme-conversion rules (Coltheart et al., 2001). In languages with transparent orthographies such as Finnish, the language studied in the present dissertation, the correspondence between written and spoken language is straightforward (Karlson, 1999), so the unique memory representations of written words may not necessarily be required for accurate reading, and reading can be based on serial decoding if it is sufficiently rapid.

The prevalent models of word recognition (Coltheart et al., 2001; Perry et al., 2007a; Seidenberg, 2005) are based on data derived from response time measurements In the present studies, eye tracking technology was used to measure participants' gaze during reading, in order to get more detailed information about the actual reading process. Eye movements during continuous reading are extensively studied and modeled (Rayner, 1998). However, these models have been mainly concerned with eye movement guidance during reading, not on the word recognition process itself. Indeed, attempts to integrate eye movement and word recognition models are rare (Hawelka, Gagl & Wimmer, 2010). In addition, few eye movement studies of reading have been conducted with dyslexic children (Hyönä & Olson, 1995; De Luca, Di Pace, Judica et al., 1999; De Luca, Judica, Borrelli et al., 2002; Hutzler & Wimmer, 2004; Trauzettel-Klosinski, Koitzsch, Dürrwächter et al., 2009). Generally, there is a risk that the findings on single word recognition may not hold for continuous reading (see e.g. Hyönä & Laine, 2002) during which several words are partially simultaneously processed. For ecological validity, it is important to test if the relevant phenomena of single word recognition are present also in continuous reading (Rayner, 1998), and vice versa.

The reading skill is achieved via a phonological decoding mechanism by applying knowledge of letter sounds to a novel letter string (Share, 1995). This effortful mechanism automatizes when letter-sound associations and orthographic word representations are being learned (Blomert, 2011; Share, 1995). Still, the nature of this early decoding is less understood and is often conceptualized in terms of word recognition models developed for adults. Also, it is clear that dyslexic readers rely more on serial processing in visual word recognition. However, especially in the context of transparent orthographies, it is still unclear whether this is due to problems in decoding, a lack of larger orthographic representations or both. With the above standpoints, the present thesis aims to provide a more detailed picture of fluent and dysfluent reading of children and adults in the transparent Finnish orthography and discusses the results in light of the current theories of word recognition, eye movement guidance and developmental dyslexia.

1.1 Single word recognition

1.1.1 General features

Most word recognition models assume that the visual perception of a word is broken down to its elementary orthographic letter features e.g. 'HA' to '| - | / - \' (McClelland & Rumelhart, 1981). These feature nodes activate letter nodes. There is evidence for readers being very sensitive to familiar letter sequences (Lima & Inhoff, 1985) as bigrams. These kind of multiletter effects may stem in parallel to letter activation either by multiletter features (e.g. // in VA (Hall, Humbreys & Cooper, 2001) or through specific letter sequence representation accessed via letter nodes (Seidenberg & McClelland, 1989). The activation between different processing levels (feature, letter, word) is assumed to be cascaded, having no thresholds (Coltheart et al., 2001). This means that the activation spreads to upper levels instantly while the activation in lower levels still increases towards a recognition threshold. Next, the orthographic representations are mapped to phonological representation of spoken language, as indisputably shown by a number of studies starting from Van Orden (1987) as reviewed by Harm and Seidenberg (2004). It is this mapping process which is central to models of word recognition. In the case of real words these phonological representations are representations of spoken words, in the case of nonwords a phonological code has to be generated (Seidenberg & McClelland, 1989; Coltheart et al., 2001; Perry et al., 2007a; Frost, 1998). When reading aloud, the phonological word or code is broken down into its articulatory elements of syllables and phonemes which further feeds down to an articulatory program of the vocal tract. From this level stems phenomena such as coarticulation as successive phonemes affect each other’s articulation, that is, their acoustic realization (Fowler & Saltzman, 1993).

Reading happens between the processes of letter encoding and the activation of phonological code. According to the dual-route model of reading (DRC; Coltheart et al., 2001), the reading of irregularly spelled words requires unique memory traces, whereas the pronunciation of regularly spelled words can be generated from print according to set of grapheme-phoneme pronunciation rules (Coltheart et al., 2001). In languages which have a completely regular writing system this correct pronunciation motivation for the dual-route architecture of reading does not exist. Division into the sublexical and lexical processes is also motivated by reasons other than the mapping between orthography and phonology. Because we encounter the same words constantly while reading, it is perhaps not surprising that memory traces of these words are formed in our brains. This becomes especially apparent in brain-damaged patients: some of them are able to read words but not nonwords while other patients do know whether a word is real or not but are unable to know its meaning (Coltheart, 2004). It is important to note that these kind of patients are found also in transparent orthographies (Cuetos, 1996; Cuetos & Labos, 2001; Laine, Niemi, Niemi & Koivuselkä-Sallinen, 1990; Beaton & Davies, 2007). The ubiquitous influence of written word frequency independent from its sublexical familiarity across orthographies also suggests that there is a mental lexicon within our brains. However, as will be discussed, it is not entirely clear whether the lexicon is orthographic or only phonological in some languages, such as in Finnish. In addition, since McClelland & Seidenberg (1989), connectionist theories of word recognition have made considerable efforts to try to develop a single-route model that can account for both word and pseudoword reading. Importantly, this approach also tries to model the nature and learning of the internal representations used in reading.

1.1.2 Word recognition theories

The two main dual-route models of word recognition, the dual-route cascaded model of reading aloud (DRC; Coltheart et al., 2001) and the connectionist dual-route cascaded model (CDP+; Perry et al., 2007a) both include an assumption that word meaning is predominantly accessed through an orthographic lexicon. According to these models, fluent readers recognize words by a holistic reading procedure (also termed a whole-word or lexical route) processing all letters in a word simultaneously, whereas novel words (pseudowords) are read by an analytic process, processing letters serially at some level of processing (also termed a phonological or sublexical route). These models differ only in respect to their serial routes: In the DRC, a phonological code is being generated by serially applying a set of pronunciation rules to a letter string. The information that some phonemes are represented by a letter sequence, a grapheme, is included in the rules. On the other hand, the serial processing in the CDP+ model stems at the orthographic processing level during which letters are serially parsed into graphemes. Thus, the serial process in the DRC stems from orthography-to-phonology mapping whereas in the CDP+ it stems from a serial shift of the visuo-spatial attention required for the graphemic parsing.

The lexical route in the DRC and CDP+ models is an interactive activation and competition model (IAC; McClelland & Rumelhart, 1981). In this model each letter activates all the words in the orthographic lexicon which share this particular letter in the same position, while inhibiting all other words. The activation speed is determined by the frequency of the word. The activation is further transmitted to the phonological lexicon in which there may also be competition between the representations of spoken words, not modeled in any of the discussed models.

Both the lexical and the sublexical routes are always activated. Working serially, the sublexical route more quickly activates the initial letters or graphemes in a word while in the lexical route the letter activations rise in parallel at an accelerating rate depending on the word frequency. Consequently, the sublexical route dominates nonword reading while the lexical route dominates word reading.

On the other hand, Frost's (1998) Strong Phonological Theory (SPT) differs from the dual-route view by assuming a mandatory phonological decoding which gives access to the phonological lexicon, and further to meaning. This phonological decoding is not assumed to have any intrinsic speed disadvantage compared to possible mediation through iconic visual word representations, which may be formed for a small set of the most frequently encountered short words. According to the SPT, the rapid decoding mechanism is consonant-driven and not always extensive, but only sufficient for lexical recognition. It is not explicitly stated whether this phonological decoding is based on serial or parallel letter processing. The important difference from the dual-route view is that in the SPT decoding always precedes lexical processing.

The connectionist models (since McClelland & Seidenberg, 1989) resemble SPT in the respect that they rely on a single mechanism for the orthography-to-phonology mapping capable of both word and pseudoword reading. These neural network models learn via exposure and feedback to produce pronunciation from print. Their knowledge is stored as distributed representations, that is, connection weights between nodes of the network. Originally these models did not include any seriality which was considered to stem from peripheral visual and articulatory processing (Seidenberg & Plaut, 1998). Plaut (1999) incorporated seriality in the orthographic letter encoding stage of his word refixation model, although words themselves were recognized via distributed representations exploiting parallel letter processing. Later, seriality was included in the generation of phonological code by setting the model to predict the remainder of the pseudoword by its beginning, based on statistical sublexical dependencies in the material the model was trained to read (Sibley, Kello, & Seidenberg, 2010). Essentially, these sequential encoders (Sibley et al., 2010) predict a gradual decrease in serial effects depending on how familiar the items are to the reader and how informative the word beginning is, as these properties speed up serial orthography to phonology mapping.

In regards to the discussed models, a central question in the present thesis is whether sublexical effects, such as the number-of-letters or syllables effects, and the influence of word uniqueness point can be found in fluent readers in real word reading. Positive findings would indicate involvement of phonological decoding as predicted by the SPT (Frost, 1998), negative findings would indicate that no phonological decoding occurs, and that letters are processed in parallel as predicted by the dual-route theories (Coltheart et al., 2001; Perry et al., 2007).

1.1.3 Word recognition in transparent orthographies

According to the Orthographic Depth Hypothesis (Frost, 1994; Lukatela et al., 1980; Lukatela et al., 1989) the more complex the mapping between the orthography and the phonology, the more visual word recognition relies on the orthographic lexicon, whereas in transparent orthographies print can be directly mapped to the phonological lexicon. This formulation was based on the findings that some word properties, such as word frequency and lexical status (word, nonword), have a larger influence on recognition speed in deep compared to transparent orthographies (Frost, 1994; Katz & Frost, 1992;

Lukatela et al., 1980; Lukatela et al., 1989). Lately, other word-level influences such as the existence of rhymes and word neighbors have been found to play a larger role in opaque than in transparent orthographies (Ziegler & Goswami, 2005). Most importantly, there is some evidence that the sublexical effects that are presumed to directly reflect phonological decoding, such as the impeding influence of word length (i.e. number of letters) to naming latencies, are larger in regular orthographies than in opaque orthographies (Ziegler, Perry, Jacobs & Braun, 2001; Ziegler, Perry, Ma-Wyatt et al., 2003b). These findings provide support for the SPT, suggesting that decoding precedes lexical processing in transparent orthographies. However, the dual-route theories may also be able to account for the larger word length effect in transparent orthographies: In a regular German orthography some phonemes are represented by four letters, which is one letter more than what is required in English. When applying the DRC's pronunciation rules more iterations are required, which increases the word length effect produced by the model (Ziegler, Perry & Coltheart, 2000). Similarly, in the CDP+, multiletter graphemes increase the time required for serial graphemic parsing, again increasing the length effect. However, in some transparent languages, such as Finnish, there is no need for graphemic parsing (CDP+) or pronunciation rules (DRC). If it turns out that the length effects are prevalent in Finnish, one explanation would be that the decoding (or mapping) is based on single grapheme-phoneme correspondences (Ziegler et al., 2001; Ziegler, Perry & Coltheart, 2003a). This possibility is supported by a French DRC modeling study (Ziegler et al., 2003a), in which it was realized that the speed of the phonological route needed to be increased to produce a serial regularity effect (that is, whether an irregular spelling lies in the beginning or in the end of a word) that was found in an empirical study.

Alternatively, many authors have entertained the possibility that units larger than letters but smaller than words may be exploited in decoding (Ferrand & New, 2003; Ziegler & Goswami, 2005; Huemer, 2009). This increase in the unit size would explain the fast nonword reading speed and reading fluency seen in transparent orthographies, while preserving the assumption of increased sublexical processing. As noted in section 1.1.1., the grouping of letters may start even from a featural level of processing. Arguably, this kind of orthographic processing itself facilitates reading. Evidence has accumulated that digrams (Marinus & de Jong, 2008; Marinus & de Jong, 2011), bigrams (Bertram, Pollatsek & Hyönä, 2004) and consonant clusters (Thaler, Urton, Heine & Hawelka, 2009) may serve as perceptual units in visual word recognition. However, according to some authors, not all of these multiletter units are functional units in orthography-to-phonology mapping (Marinus & de Jong, 2011).

One candidate for this type of sublexical large unit is a syllable, which is also a functional unit in most spoken languages. Of course, frequently occurring in natural texts, syllables may also be an orthographic unit. Further, syllable frequency studies have found that the initial syllable has a special function in a lexical search from orthographic or phonological lexicons (Carreiras, Ferrand, Grainger & Perea, 2005), suggesting that the syllable may also be a functional unit for the lexical route. Assuming that the sublexical route would process syllables serially, the number of syllables should have an impeding effect on reading. Currently, the impeding effect of the number of syllables on pseudoword or infrequent word reading has been found in English (Jared & Seidenberg, 1990; New, Ferrand, Pallier & Brysbaert, 2006), in French (Ferrand & New, 2003; Ferrand, 2000) and in German (Stenneken, Conrad & Jacobs, 2007). The DRC model is restricted when reading monosyllabic English words, but some authors have entertained the possibility that the sublexical route would work at the level of syllables as well (Ferrand & New, 2003). An extension of the CDP+ model, the CDP++ model (Perry, Ziegler & Zorzi, 2010), is designed for reading bisyllabic words. In this model the syllables are not mapping units but are parsed, like the graphemes, by the serially shifting visuo-spatial attention mechanism, for the purpose of phonological stress alignment. A connectionist multi-trace memory model (MTMM; Ans, Carbonnel & Valdois, 1998) makes an explicit prediction that if the word is not in the orthographic lexicon, it will be read aloud syllable-by-syllable, predicting routinely the number-of-syllable effect for nonwords.

1.2 Continuous reading

Human vision is precise only in the fovea covering approximately two degrees of the visual field. Thus, visual acuity provides a strong constraint for visual word recognition (Rayner, 1998). This means that in a typical text reading setting words having more than eight letters do not fit fovea and consequently either need to be fixated on for a longer time or even refixated on (Rayner, 1998). The actual visual uptake of information is a rapid (less than 50 ms) parallel process (Rayner, 1998) – very likely not achieved via a left-to-right visual scan (Inhoff, Eiter, Radach & Juhasz, 1989; Adelman, Marquis & Sabatos-DeVito, 2010) except in the case of long words where progressive refixations are required due to the visual acuity constraint (Vergilino-Perez, Collins, Doré-Mazars, 2004). Importantly, a visual crowding effect also increases hand-in-hand with visual eccentricity – the visual interference of nearby objects (Bouma, 1970). The visual acuity constraint and crowding effect can be seen as providing the basic limitations for the amount of information gathered during an eye fixation (Rayner, 1998) and for human reading speed in general (Pelli et al, 2007).

While you read this sentence you are constantly making rapid eye movements called saccades, lasting only few tens of millliseconds, followed by longer pauses called eye fixations. During the fixations, which last approximately 200 ms, eyes stay relatively still, visual information is being gathered and next saccade is being planned (Rayner, 1998). It seems that the eye movement guidance and word recognition systems are rather distinct cognitive systems (Inhoff et al., 2003). Saccade targeting is based mostly on coarse spatial information such as spaces between words (Inhoff et al., 2003; Rayner, 1998). The target for an inter-word saccade approximates the center of the next word, a place that provides the best visibility of the word’s letters (Rayner, 1998). As said, the refixations are largely made as a function of word length, presumably due to the visual acuity constraints (Vergilino-Perez et al., 2004). There is evidence that even two saccades may be preplanned: refixations on long words are preplanned before entering the word (Vergilino-Perez et al., 2004). The span for the saccade planning is about 15 letters to the right of a fixation, while the span for the word recognition system is smaller, extending only 7-8 letters to the right and 3-4 letters to the left from a fixation point (Rayner, 1998). It is believed that these spans are limited by attention (Morrison & Rayner, 1981), and best expressed as how many letters can be simultaneously processed, although the visuo-spatial influences, such as visual acuity and crowding, are not completely ruled out (Miellet, O’Donnell & Sereno, 2009).

Research has shown that most of the time a word needs to be fixated on or at least attended to to be recognized (see Reichle, Pollatsek & Rayner, 2006). This is mainly due to the fact that next-to-fixated on word typically falls into parafoveal vision having poorer visual acuity (Rayner, 1998). Although a complete recognition may be difficult from the parafovea, a preprocessing of the next word is however taking place. The amount of this preprocessing is largely dependent on how near the current fixation point of the upcoming word is, and how easy the currently fixated on word is (Hyönä, 2011). There is evidence that at least the initial letters of a next word are subject to preprocessing (Lima & Inhoff, 1985) leading even to some phonological activation (Pollatsek, Lesch, Morris & Rayner, 1992; Miellet & Sparrow, 2007). However, preprocessing of the word meaning seems to be very limited at best (Reichle, Vanyukov, Laurent & Warren, 2008).

The most influential model of eye movement control in reading is the E-Z (easy)-reader (version 9; Reichle et al., 2006). Crucially, this model assumes that the saccade targeting, requiring no attention, is based on the coarse visuo-spatial information of word boundaries, whereas two-stage lexical processing requires direct attention. The first lexical stage is conceptualized as a fast familiarity check including the lexical search of word forms, whereas the latter stage consists of higher order processing such as contextual comprehension. The familiarity check can inform the saccade targeting system that the word will be recognized and the programming of the next saccade can be initiated. Another influential model is the SWIFT model (Saccade-Generation With Inhibition by Foveal Targets; Engbert, Nuthmann, Richter & Kliegl, 2005), in which the attention-visibility gradient extends over several words. Finally, the oculomotor models (McConkie, Kerr, Reddix & Zola, 1988) try to explain the readers' eye movement behavior resulting from low-level perceptual and high-level strategic factors, so the eye movement behavior may not be always tied to the processing of currently looked words. The models of eye movement control in reading and word recognition have not been fully integrated, which would certainly be appreciated in developing a comprehensive framework for understanding reading. Hawelka et al., (2010) suggested that in dual-route terminology the first lexical stage of the E-Z reader may correspond to the orthographic lexicon and the later stage to the phonological lexicon, although no empirical evidence for this analogy was provided. A good example of the need for theoretical integration is the different explanations given by the word recognition and the eye movement models for temporal word length. The former type of models (DRC; CDP) stress linguistic-attentional factors, whereas the latter type of models (E-Z reader; SWIFT) lean on the visual acuity hypothesis – that letters farther from a central fixation point would suffer more visual degradation, which is assumed to slow down the speed of letter encoding.

1.3 Reading development

Learning to read is based on the mastery of an alphabetic principle – the regularity of the mapping between the spoken and the written language (Ehri, 1987; Share, 1995). Orthographies vary greatly in the complexity of this mapping, causing a substantial variation in the ease of reading acquisition across orthographies: in opaque orthographies learning to read accurately takes several years (Seymour et al., 2003), whereas in simpler orthographies reading acquisition can happen in months (Seymour et al., 2003). Knowing the grapheme-phoneme (G-P) correspondences it is usually possible to unravel the spoken forms of even unfamiliar written words. This is called a phonological decoding mechanism. Phonological decoding is an efficient self-teaching mechanism which enables the reader to learn new words (Share, 1995). Therefore it is important that children are explicitly taught to phonologically decode words by the phonics method (Rayner et al., 2001). In English, a small amount of common exception words have to be learned by heart even by beginning readers. Taught by a sight-word method, readers learn to recognize these words as visual shapes, or logographs (Ehri, 1987). Specific orthographic word representations also begin to be represented in memory rather early in reading development (Martinet, Valdois & Fayol, 2004). According to some estimates even a few repetitions may be sufficient for orthographic learning to occur (Share, 2008).

The self-teaching hypothesis contains the idea that the development of reading is more item-specific than characterized by different reading stages (Ehri, 1987). However, the studies behind this theorizing have been concerned with reading accuracy instead of the temporal aspect of the children's decoding. Share (1995; 2008) have argued that early decoding remains poorly understood. In contrast to the fluent sublexical processing of adults, early decoding is probably a much more comprehensive cognitive action, requiring several recognition events even of single letters, keeping the corresponding phonemes in the working memory, blending the sounds together and checking and monitoring the response. Recently, Blomert and colleagues have studied early reading development extensively, focusing on the automatization of grapheme-phoneme associations in the relatively transparent Dutch orthography. Their main discoveries were that having learned the letter names, the automatization of the G-P associations is required for reading acquisition, that the G-P associations are active even in adult reading, and that individuals with dyslexia seem to have major problems in attaining these automatized G-P associations (Blomert, 2011). Blomert ends his review by asking whether the decoding also develops by learning to decode larger units than the G-P associations. The present thesis examines whether the syllable is such a large unit in developing reading, as has been recently argued by Gagl, Hawelka & Wimmer (2010) and Häikiö (2011), who both found a temporal number-of-syllable effect on readers' eye movements only in the younger group (second grade) of their subjects. Descriptively, the development of reading fluency and word recognition speed has been shown to continue towards adolescence even in transparent orthographies (Zoccolotti, De Luca, Di Filippo et al., 2009). This development is accompanied by a concurrent increase in the perceptual span of letters as shown by a Finnish eye tracking study (Häikiö, Bertram, Hyönä & Niemi, 2009).

1.4 Developmental dyslexia

Developmental dyslexia is characterized as a failure to develop an effortless reading skill (Fletcher, 2007). More specifically, this deficiency is already present at the level of single word recognition (Vellutino et al., 2004; Rayner et al., 2001). However, there does not seem to be problems in dyslexics' eye movement guidance per se (Rayner, 1998), although some anomalies have been reported in binocular coordination of the eyes (Jainta & Kapoula, 2011), in an excessive amount of visual crowding (Martelli, Di Filippo, Spinelli & Zoccolotti, 2009) or in visuo-spatial attention (Vidyasagar & Pammer, 2010). In opaque orthographies dyslexics have difficulties in reading accuracy and speed, especially in nonword reading (Rack, Snowling & Olson, 1992), whereas in transparent orthographies accurate reading skills are typically attained but the reading speed remains slow (Wimmer, 1993). Dyslexics' word recognition is characterized by increased sublexical processing as shown by the dramatically larger word length effect relative to normally reading peers, already apparent in single visual word naming (Ziegler et al., 2003b; Zoccolotti, De Luca, Di Pace et al., 2005; Martens & de Jong, 2008) and lexical decision response times (Martens & de Jong, 2006; Filippo, De Luca, Judica et al., 2006). Still, in these behavioral studies a smaller word than nonword length effect and a large lexicality effect is typically seen also in dyslexic individuals, raising the question whether dyslexics possess some capabilities for holistic processing or whether the phonological decoding of pseudowords is only prolonged due to absent lexical support.

The few eye movement studies conducted with developmental dyslexics since Hyönä and Olson (1995) have been especially revealing by demonstrating a substantially larger word length effect in the number of fixations relative to typically reading peers (De Luca et al., 1999; De Luca et al., 2002; Hutzler & Wimmer, 2004; Trauzettel-Klosinski et al., 2009; Hatzidaki, Gianneli, Petrikas, 2010). Most importantly, although not pinpointed by the authors, these studies show that the length effect in dyslexics in word and nonword reading is equally steep in number of fixations. Instead, the lexicality effect seems to be pronounced in fixation durations. This pattern of results provides the strongest evidence for the view that dyslexic reading is characterized by almost a letter-by-letter reading style.

An influential explanation for these findings has been that dyslexics have a deficient lexical reading route (Zoccolotti et al., 2005) and are consequently reading by the sublexical route. Lately, Bergmann and Wimmer (2008) have suggested deficits also in sublexical route and in the "orthographic evaluation" process within the lexical route. It may be that the entire word recognition system including the whole-word route and decoding route is affected, perhaps due to some lower level visuo-orthographic deficit (Zoccolotti, De Luca, Judica & Spinelli, 2008; Bosse et al., 2007). Finally, it may be that the initial problem lies in the decoding route, or put differently, in the automatization of G-P associations (Blomert, 2011), which also prevents the proper establishment of the whole-word route.

Attempts to remediate dyslexia have been more successful in respect to reading accuracy than to reading speed or fluency (see Huemer, 2009). Dyslexic children benefit from training in phonological awareness and from specialized phonics instruction (Ehri, Nunes, Willows et al., 2001), presumably via strengthening of G-P rules or associations, and formation of orthographic word representations. Based on the skill automatization theory of LaBerge and Samuels (1974), a repeated reading method (Samuels, 1979) was developed for reading fluency intervention. The basic idea in this method is that the automatized recognition of words frees attention resources for comprehension processes. However, practicing every word in a language would be an exhaustive task. The repeated reading of sublexical parts holds the promise that the possible benefit will generalize to all other words containing that sublexical part (Huemer, Aro, Landerl & Lyytinen, 2010). Promisingly, positive albeit small generalization effects have been obtained with consonant clusters (Thaler, Ebner, Ladner & Wimmer, 2004), and syllables (Tressoldi et al., 2009; Huemer et al., 2010; Ecalle et al., 2009). A study with an adult dyslexic subject has shown that repetition can reduce word length effects in response times, which is only suggestive of a shift from sublexical to whole-word recognition (Maloney, Risko, O'Malley & Besner, 2009). Few studies assessing the effect of repeated reading on dyslexic children's word length effect have not found reliable reductions, suggesting that the serial G-P reading strategy has not been relieved (Martens & DeJong, 2008; Judica, De Luca, Spinelli & Zoccolotti, 2002).

1.5 Reading Finnish

The present research was conducted in the Finnish orthography, which differs from English in number of ways. Most crucially, Finnish is a completely transparent language both in the directions of orthography-to-phonology and phonology-to-orthography. There are only 24 phonemes represented by 24 letters, with the exception of grapheme ng (Aro, 2006). In English there are 50 phonemes and approximately 1500 specific G-P connections to learn (Goswami, 1995). Finnish is an agglutinative language with a rich morphology and productive compounding. Theoretically, there may even be 2000 word forms for nouns and 12 000 for verbs (Karlson, 1999). Consequently, Finnish words are often long, extending past foveal vision (Bertram & Hyönä, 2003). It is clear that sublexical processing plays an important role in reading Finnish, especially when reading morphologically complex words (Hyönä, Bertram & Pollatsek, 2004). In principle, it is possible that Finnish is read by a simple letter-phoneme conversion mechanism. This may not, however, be the case. Orthographic transparency seems to promote only phonological decoding but not to completely prevent the development of the lexical route (Katz & Frost, 1992). Studies conducted in Finnish with morphologically complex words (Hyönä et al., 2004; Bertram et al., 2004) suggest that there are word representations for relatively frequent inflected word forms. Instead, more complex words are subject to morphological decomposition in which constituents are first recognized serially, providing an access to the meaning of the complex word. However, such representations may be phonological and whether there are orthographic lexical representations for simple words in Finnish has not yet been thoroughly studied.

Finnish is a syllable stressed language with the word initial syllable always being stressed (Karlsson, 1999). The syllabification in Finnish is determined by simple rules of denoting a syllable boundary before every sequence of a single consonant followed by a vowel, and denoting a syllable boundary between vowels not constituting a diphthong (Karlsson, 1999). Syllable CV-structures are limited to ten and the number of different syllables to 3000 (Karlsson, 1999), being also in this respect one of the simplest European languages (Seymour et al., 2003). Syllables seem to be a good candidate for decoding in Finnish because they are limited in number, frequently occurring, easily parsed and required for fluent pronunciation.

A transparent orthography supports the acquisition of reading, which happens much faster in Finnish than, for example, in English (Seymour et al., 2003). Reading education in Finnish is systematically based on phonics instruction. Nearly every child learns to decode in the first grade (Lerkkanen, 2007; Holopainen, Ahonen & Lyytinen, 2001) almost in an overnight fashion (Aro, 2004). Already in the second grade literacy curriculum focuses on fluency and reading comprehension. Reading development rapidly follows the learning of letter names (Lyytinen, Aro, Eklund, Erskine et al., 2004; Torppa, Lyytinen, Eklund et al., 2010), and beginning readers seem to not make use of word analogy cues such as rhymes in reading (Holopainen, Ahonen & Lyytinen, 2002). Moreover, reading and spelling skills are taught simultaneously and children typically acquire both skills confidently. Syllabification has been found to be instrumental for learning to read and is widely used in early reading education; syllabification is explicitly marked in today's early reading materials (Aro, 2004). In Finnish preschools, children usually learn the phonological awareness of syllables. Then in the first grade, after having learned the letters and the alphabetic principle, children are taught to phonologically decode hyphenated words in syllable-by-syllable fashion by "sliding" their articulation while recognizing the hyphenated syllables (Lyytinen, Erskine, Tolvanen et al., 2006; Lerkkanen, 2007).

As in other transparent languages (Seymour et al., 2003), reading problems in Finnish manifest primarily as slow reading speed (Leinonen, Müller, Leppänen et al., 2001), although errors are being made when reading difficult long words and pseudowords (Aro, Eklund & Kairaluoma, 2010). In the Jyväskylä Longitudinal study of Dyslexia (JLD), children were followed from birth to Grade 9 enabling detailed predictive analyses of reading development. In sum, the results of the JLD project (Lyytinen et al, 2006) suggest that reading acquisition can be predicted to some extent from early language and phonological awareness skills (Puolakanaho et al., 2007) supplemented by early language activities (Torppa, 2007). Naming speed and letter knowledge are the best predictors of reading fluency in Finnish (see Torppa et al., 2010). Newborn electrophysiological brain responses also show positive correlation to later language and even reading skills (see Lyytinen, Guttorm, Huttunen et al., 2005).

1.6 Methodological considerations

Word recognition models have been largely based on response time data derived from naming (Coltheart et al., 2001) and lexical decision tasks (Seidenberg & McClelland, 1989). This methodology is relatively easy to use and is also suitable for studies with children: Custom-built software displays a written word on a computer screen. In the naming task a subject names aloud a word displayed while an electronic voice onset trigger registers a response onset time. In the lexical decision task the subject is asked to decide whether a word is real or not by pressing a yes or no button. In English, even the last letter in a word can affect how the initial letter is pronounced. Accordingly, there is evidence that in English adults initiate their naming response only having completely processed an item (Rastle, Harrington, Coltheart & Palethorpe, 2000). In transparent orthographies the later letters in a word do not influence the pronunciation of the earlier letters, making it a viable strategy to start the response while still processing the word. If this is true, our phonological manipulations should affect also the naming response durations, in addition to the response onset latencies.

Reaction times are end-point measures of cognitive processing, providing little if any information about how the word was actually processed. For this reason, complex designs such as priming are commonly exploited. The disadvantage of these complications is that additional assumptions, for example about the mechanism of priming, are required. Instead, eye movement recordings of reading provide detailed online information about natural reading. More specifically, the spatial location of a fixation shows where the attention is allocated and the high temporal resolution provides a means to separate the time course of processing. According to Rayner (1998) the major classes of word-based eye movement measures are fixation frequency, fixation duration and saccadic measures. The first-pass measures (i.e. the first encounter with the word) reflect the actual word recognition process whereas the second-pass measures (i.e. the return to already fixated or skipped word) reflect challenges in integrating the word into context or checking whether the word was read correctly. Proficient adult readers typically make only one fixation on a simple word making the single fixation duration perhaps the most interesting measure. The longer and more complex the word is, the higher the probability to make a progressive refixation into the word. As initial perception of the word have been gained during the first fixation, the refixations are typically shorter in duration. Therefore, the summed duration of all first-pass fixations to a word, i.e. gaze duration, reflects the overall amount of processing devoted to a word. Poorly reading children may fixate on almost every letter in a word, making the number of fixations a useful measure of the serial reading strategy. Combined with spatial information, one can capture the entire reading process: whether the word was fixated on or skipped, what the landing position of the first fixation on a word was, how many fixations were made on a word, what the duration of these fixations was, how the gaze proceeded within the word and whether the reader returned to an already once read word.

Most of the eye movement research in reading has been interested in fluent reading and very little has been concerned with dyslexia and early reading stages (Rayner, 1998). There is an apparent reason for this, as eye tracking with children as subjects is a challenging task. Current eye trackers are based on pattern recognition of the pupil and infrared light reflection from the cornea on high-speed eye video, so unrestricted visibility to an open eye, proper visual adjustments of video camera, and proper settings for the eye tracking software are prerequisites for a successful measurement. All of these factors can be subject-dependent, thus requiring a skilled experimenter. Even then, the data of some children and adults are lost due to restlessness or anatomical properties of eye for example, such as drowning eyelids and eyelashes falling over the pupil.

Fixations and saccades are detected from raw data by the manufacturer's or researchers' own algorithms which requires the researcher to set up a minimum saccade velocity threshold. The value should be higher than noise but lower than the maximum velocity of real saccades. In the AOI analysis, fixations are classified according to the stimulus coordinates. In the present studies the stimulus presentation software was not integrated with the eye tracker software, so the stimulus coordinates were derived from the screen captures and fed into spreadsheet syntaxes (SPSS). Also the dependent variable calculations were made by conditional clauses and the data processing functions of SPSS.

1.7 Aims of the Studies

The aim of this dissertation was to attain a good understanding of the recognition of simple words among fluent and dysfluent adult and child readers in the fully transparent Finnish orthography. The main research question was: what are the relevant linguistic decoding units in reading? According to the dual-route view of reading, these units are letters for the sublexical route and words for the lexical route. Therefore, the number of letters and the lexical status were included as specific markers for workings of the sublexical and lexical routes. However, in recent years, the syllable has also been suggested as being a sublexical decoding unit, so the number of syllables within words was also manipulated.

In Study I, the eye tracking method was exploited to get an overall view of the reading units exploited among the extremes of reading skill, in fluent adults and in dysfluent child readers. The measurement of the number of fixations was of special interest as it was to reveal how readers analytically process words. Further, the repeated reading of the same items provided a dynamic window to orthographic learning. Dysfluent readers were expected to show a deficiency in learning the orthographic word representations and continue to read the words using the sublexical reading strategy.

In Study II the possibility that syllables are important decoding units in early reading was assessed in typical and dysfluent second grade readers. To avoid restlessness-induced problems in tracking young children's eye movements, traditional naming and lexical decision tasks were employed. The main research questions were whether the typical readers have already established holistic word recognition and whether the dysfluent readers show the characteristically serial reading style. Second, it was studied whether the syllable is a relevant decoding unit for either of the groups. Third, it was of interest whether the dysfluent readers were more impaired either in the naming task stressing phonological processing or in the lexical decision task that required more elaborate lexical processing. Finally, naming onset and offset response times were separated to attain new information about the children's phonological decoding strategies.

Study III investigated whether the various word length effects routinely seen in eye movement measures of natural reading reflect the influence of the number of letters or the spatial width of the words. This question is central for understanding whether word length effects stem from visuo-spatial or linguistic processes. Previous research suggests that inter-word saccades are programmed based on the words' spatial width whereas fixation durations may be affected by both the number of letters and the spatial width. As the manipulation affecting the complex set of dependent variables was novel, the issue of reading skill was omitted in this pioneering work, but is currently in preparation.

Study IV was designed to investigate if letters and syllables are used for lexical searches, irrespective of whether they are a unit of serial decoding or not. For this objective, the word length effect was seen as problematic, as it is confounded by peripheral influences such as articulation or differences in the visual size of the stimulus words. The solution was to study the influence of word uniqueness and pseudoword deviation points on the lexical decision latencies. The uniqueness and deviation points refer to a letter position, at which no other existing word has the same word beginning. If the lexical search is serial, the words having an early uniqueness point would be recognized faster than the words having a late uniqueness point. A pilot study was conducted only with fluent adult readers, whereas the second experiment compared fluent and dysfluent adult readers.

2 SUMMARY OF THE RESULTS

2.1 Study I: Sublexical effects of repeated reading

According to the dual-route view of reading, fluent readers process words in a holistic manner and pseudowords in an analytical manner, whereas dysfluent readers process both words and pseudowords by the analytic strategy. The processing style would be best revealed by the registration of eye movements and measuring the number of fixations made per linguistic unit, although refixations are also governed by other factors, such as word frequency (Rayner, 1998). The first study aimed to replicate the eye movement findings of the increased word length and lexicality effects in dyslexic readers seen in other transparent orthographies (De Luca et al., 1999; De Luca et al., 2002; Hutzler & Wimmer, 2004; Trauzettel-Klosinski et al., 2009; Hatzidaki et al., 2010). In addition, the influence of the number of syllables in a pseudo/word independent from the number of letters was studied. The prediction that dysfluent readers have problems in orthographic learning was assessed via repeated reading of the same items. Orthographic learning would be shown by a reduction in the number of fixations per manipulated orthographic unit.

2.1.1 Methods

Nineteen fluent adults and eighteen dysfluent children (below 1 SD from age-level norms in reading skill, while performing at a normal level in a general intelligence test) participated in the study. Ten pseudowords and ten words were repeatedly read aloud ten times from a computer screen while leaning on the forehead rest of the eye tracking equipment. For the construction of a repetition-factor with a sufficient number of observations, the ten repetitions were averaged into two blocks of five repetitions. To assess the influence of the number of letters, there was a pair of four, six and eight letter bisyllabic items and to assess the influence of the number of syllables there were a pair of bi- tri- and quadrisyllabic eight letter items. Of special interest was the number of fixations per item, a hypothesized index of the processing style. In addition, the gaze duration shows the overall reading time whereas the average fixation durations reflect the efficiency of processing.

2.1.2 Results

The fluent adult readers showed a smaller word length effect than pseudoword length effect in the number of fixations. Repetition reduced their pseudoword length effect. The dysfluent child readers showed an equal word and pseudoword length effect in the number of fixations and repetition did not reduce this ratio. The same pattern of results was found in the gaze duration. However, the dysfluent children showed a clear repetition-induced reduction in average fixation durations on the words, but not on the pseudowords. Manipulations of the number of syllables did not produce notable effects.

2.1.3 Conclusions

The results were in line with previous studies indicating an extremely serial and fragmented reading strategy for dysfluent readers. This strategy was not relieved by instant repetitions as was the case with the fluent adult readers. The adult readers showed specialized processing styles for pseudowords and words and evidence for the rapid learning of new orthographic pseudoword representations. The results are in line with the views shared by both the dual-route and connectionist models of reading, predicting that word recognition processes go through a major change during the learning of new orthographic items. Repetition seemed to support the usage of lexical information in the dysfluent children, but this only speeded up their serial reading style. The fact that the children continued to decode the words in an exhaustive manner even when having a fairly good idea what the word would be, this finding raises the question of whether the serial strategy partially reflects a careful, mistake-avoiding reading strategy.

2.2 Study II: The role of letters and syllables in developing reading

Study I provided detailed insight about eye movement behavior during word recognition in the extremes of reading skill. Study 2 aimed to get a more detailed understanding of typically and poorly developing reading in Finnish. To study the question of the decoding unit, lexicality, the number of letters, and the number of syllables in an item were orthogonally manipulated. To get insight about the role of these units in lexical recognition and mere decoding, a lexical decision and a naming task were assigned, tapping these processes respectively. As Huemer (2009) and Share (1995) have stated, the process of phonological decoding remains somewhat underspecified. Here, a means to separate an assembled, silent decoding from an online decoding aloud is suggested. In transparent orthographies, the later letters in a word do not influence the pronunciation of earlier letters, enabling an online reading strategy according to which a word naming response is initiated before generating a full phonological code of the item. Separation of the onset time and the offset time of response in a naming task would reveal this strategy usage.

2.2.1 Methods

Out of the 40 second-grade children tested, 13 were classified as dysfluent readers (DYS) performing below -1.25 SD in composite scores of three reading tasks, whereas 23 children who performed above - 1 SD in these tasks constructed an age-matched control group. The children read four-letter bisyllabic, six-letter bisyllabic and six letter trisyllabic words and pseudowords, 25 of each, presented one-by-one on a computer screen. Words were controlled for frequency and pseudowords were constructed from the words by replacing two letters, retaining the CV-structure of the base word while conforming to Finnish phonotactics. In the naming task, the children read the items aloud while a computer recorded their articulation and a voice key registered the response onset and offset times. In the lexical decision task, the children were asked to decide whether an item is a real Finnish word or not, by pressing a corresponding button. Only the response times of correct responses were analyzed.

2.2.2 Results

The children responded with a high mean accuracy rate of 90%. The typical readers showed clear lexicality and number-of-letter interactions in both tasks and no signs of number-of-syllable effects. The word length effect was stable only in the naming task, not in the lexical decision task. There were minor influences of stimuli properties in the response duration measure in the naming task.

The number of letter and lexicality manipulations had generally larger impeding influence on DYS reading irrespective of the task. Dysfluent readers were more delayed in the lexical decision than in the naming task. The number of letter effect was substantial also in the word reading conditions in the DYS group. The DYS group showed a number of syllables effect in the lexical decision task but not in the naming task. In the naming task, the DYS group showed generally lengthened response durations and this was especially prominent for the longer pseudowords. Further, additional data with a few dyslexic subjects showed that when the words and the pseudowords were presented in a mixed order, the lexicality and length effects were present only in the response durations, not in the response onset times.

2.2.3 Conclusions

Generally, the results replicated the pattern of results derived from other transparent orthographies, that is, a steep pseudoword length effect, an absent word length effect and larger responses of dysfluent readers to length and lexicality manipulations. These findings are in line with the dual-route architecture of reading and the view that dyslexics have problems in establishing the lexical route. The reading of pseudowords was also greatly compromised, which is suggestive of a problem in phonological decoding as well. Developmentally, poor decoding skills may cause a delay in or completely prevent the establishment of the whole-word recognition facility. The typical readers assembled the phonemes mostly before initiating the response. The dysfluent readers relied on online phonological decoding especially when reading the long pseudowords, suggesting that at this stage of reading development, assembling the phonemes together is still a challenging task for dysfluent readers. Further, the number of syllables effect was specifically related to the requirement to make a lexical decision, which may indicate that when required to fully recognize a word, poor readers first assemble phonemes into syllables, and only then the syllables into words. As the typical readers did not show impeding syllabic effects, such syllabic decoding seems not to be present in more fluent reading, which may be more based on the lexical route, at least when reading simple nominal words in Finnish. Finally, as dysfluent readers performed relatively better in the naming than in the lexical decision task, and did not show a consistent number-of-syllable effect in the naming task, it may be that the naming measures did not capture the dysfluent readers' reading process as entirely as the lexical decision task did. This conclusion fits the Finnish early reading education during which children are taught to decode words online and conduct phonological assembly and recognition on the fly, or only as an end result of the decoding aloud process.

2.3 Study III: Dissociating spatial and letter-based word length effects

Previous eye movement research of reading has confounded the number of letters in a word and the spatial width of a word due to standard usage of a monospaced font, in which each letter covers the equal spatial width. As the spatial information of word boundaries is believed to govern saccade programming while the number of letters may affect fixation durations, it is problematic that the independent influence of these factors has remained elusive. Here, by an innovative exploitation of varying letter width of a proportional font, the number of letters in a word is manipulated while keeping the spatial width of the words equal. This manipulation should reveal the possible unique influence of number of letters in a word to eye movement behavior in reading. In addition, the standard word length effect in monospaced font served as a control condition for studying the influence of words' spatial width on eye movement behavior in reading. The results were discussed in terms of eye movement control models of reading and the dual-route model of word recognition.

2.3.1 Methods

As the manipulation was novel and the set of dependent variables was complex, a study with only fluent adult readers was considered to have substantial scientific content. While leaning on forehead and chinrests of eye tracking equipment, 35 fluent adult readers (university students) silently read stimulus sentences presented one-by-one on a computer screen. After each sentence they answered a yes-or-no question based on the sentence. In the middle of the sentence there was a four or six letter long target word (noun). The task included 30 items of each length in proportional font and 20 items of each length in monospaced font. The target words were controlled for sentence context, word frequencies and for pixel width, except that the six-letter monospaced words were deliberately wider. First-pass fixation duration measurements, preview fixation duration, fixation frequency and fixation location measurements of the target words were analyzed. In a post-hoc analysis the specific role of spatial width to saccade targeting was studied by comparing narrow and wide proportional font target words. To study the influence of font on reading, eye movement measures were also analyzed at the sentence level, including the mean number of letters traversed during a saccade.

2.3.2 Results

In the proportional font, landing position, initial saccade amplitude (saccade size in pixels) and probability to skip a word were unaffected by number of letters, whereas in the monospaced font, these saccadic measures reflected the increased spatial width. The special influence of spatial width on saccade targeting was confirmed in the post-hoc analysis comparing narrow and wide proportional font words: skipping probability was decreased by a rate of percent per pixel. Interestingly, the skipped words were regressed at a random level while only every fourth first-pass fixated on word was regressed. The sentence level analysis revealed that the same number of letters was travelled during saccades in both fonts and that fixation durations were generally shorter in the monospaced font.

There was a small 5 ms per letter influence on fixation duration measures of the target words, irrespective of the font type. The refixation probability was not reliably affected by the modest manipulation of word length but showed a trend for the six-letter monospaced words of being more frequently refixated. The preview fixation duration did not show any response to the target word length or width. The fixation durations were generally shorter on the words presented in the monospaced font.

2.3.3 Conclusions

For the first time, the influences of words' spatial width and number of letters were successfully dissociated from each other in a completely natural reading setting. The results provide novel support for the existence of independent systems for determining where and when to move the eyes while reading. A new finding, the decision whether to skip a word seems to be determined by spatial width, not by the number of letters. Letters may be recognition units for foveally fixated words, but there were no of signs of parafoveal preprocessing of letters. This finding supports the view that attention is allocated serially between the words, as predicted by the E-Z reader model. The fixation duration results are in line with the dual route view of reading. However, the word length effect in fixation duration may also be explained by visual factors. In monospaced fonts, longer words may have received prolonged fixations as encoding letters farther away from a fixation point may require more time due to the poorer visual acuity in parafovea. In proportional fonts, letter encoding of six letter words may have been slower due to the visual crowding between letters. Finally, as the number of letters traversed during a saccade was equal in both fonts, the perceptual span seems to be determined mainly by number of letters and not by visuo-spatial factors as letter spacing.

2.4 Study IV: Word uniqueness and deviation point effects

In Study III, the word length effect found in fixation durations may have resulted from visual processes or from phonological decoding. However, there is a way to study seriality in visual word recognition at the lexical level as well, with no perceptual differences in stimulus materials. A seldom studied serial factor in words is the word uniqueness point, which refers to a letter position at which no other word in a language has a similar word beginning. The pseudoword deviation point refers to a letter position at which no existing word has a similar beginning. If letter processing in Finnish is serial, an impeding effect of the word uniqueness point would be expected in word reading, as well in pseudoword reading.

2.4.1 Methods

The word uniqueness, pseudoword and nonwords deviation points were studied in lexical decision tasks. The first experiment was concerned with whether pseudowords with word-like beginnings are responded to slower than pseudowords with word-like endings. This question was studied in a letter-by-letter fashion to determine the exact length of the word beginning that is capable for a lexical activation. In the second study, 20 fluent and 12 dysfluent readers were compared in a lexical decision task, in which words, pseudowords and nonwords (containing an illegal foreign consonant either as a first or last letter) with early and late differentiation from true words were presented.

2.4.2 Results

The results of the two experiments produced a consistent pattern of results: In the first study the fluent readers showed a faster response time on pseudowords beginning with a phonotactically legal syllable with which no existing word begins. In the second study neither fluent or dysfluent readers showed the influence of the word uniqueness point, but showed again a clear inhibitory pseudoword deviation point and, in addition, a clear facilitory nonword deviation point effect. The response times of the dysfluent readers were generally slower, and even slower to the pseudowords, whereas there were trends only for larger serial deviation point effects.

2.4.3 Conclusions

The strong effect of the pseudoword deviation point suggests that the lexical search for pseudowords is conducted strictly serially or dominated by the initial syllable (Álvarez, Carreirea & De Vega, 2000). Häikiö (2011) and colleagues studied the influence of rare bigrams at the syllable boundary on eye movements in the autumn and spring semesters of second-grade Finnish readers. They found an effect only in the autumn term. Because beginning readers are assumed to rely predominantly on phonological decoding, their findings also support the view that syllables are functional reading units only for the phonological route in Finnish. It remains to be studied whether the syllable is a relevant reading unit when reading longer words that are subject to sublexical processing due to the visual acuity limitations of the human vision, and when reading inflected word forms containing several sequentially ordered morphological endings. In the present study, no word uniqueness point effect was found, supporting the prevalent view (Coltheart et al., 2001; McClelland & Rumelhart, 1981) that the letters of real words are processed in parallel. The facilitative influence of the nonword uniqueness point may be due to the fact that a foreign consonant at the end of the word violates the Finnish phonotactics more heavily, and is in line with the general view that orthographic processing precedes phonological and lexical processing. The dysfluent readers did not show signs of increased serial processing but generally slower response times, suggesting that adult dyslexia is characterized more as a general slowness in word recognition than increased reliance on the serial processing, which was the case with dyslexic children.

TABLE 1 Summary of the main research findings

				Words		Pseudowords	
Study	Reading task	Skill	Age	Let	Syl	Let	Syl
1	Lists, aloud	Fluent	Adult	+	o	+	o
		Dysfluent	Grade 5	+	o	+	+
2	Naming, single items	Fluent	Grade 2	+	o	+	o
		Dysfluent	Grade 2	+	o	+	o
	Lexical decision	Fluent	Grade 2	o	o	+	o
		Dysfluent	Grade 2	+	+	+	+
3	Natural sentences, silent	Fluent	Adult	+			
4	Lexical decision	Fluent	Adult	o	o	o	+
		Dysfluent	Adult	o	o		+

+ = Found effect on reading; o = Null effect on reading; Empty space = unstudied

3 GENERAL DISCUSSION

3.1 Units and routes for fluent reading in the transparent Finnish orthography

3.1.1 Discussion of empirical findings

Fluent word recognition in Finnish was, similarly to previous findings in other orthographies (Weekes, 1997; Martens & de Jong, 2006; 2008; Di Filippo et al., 2006; De Luca et al., 2009; Zoccolotti et al., 2008), mainly characterized by a large lexicality effect and by a smaller number-of-letter effect for words than for pseudowords. A central question was whether sublexical effects, such as the number of letters or syllables, or uniqueness point effect can be found in fluent readers. A lack of these effects can be viewed as a sign of holistic word recognition conducted via parallel letter processing (Coltheart et al., 2001). It was hypothesized that due to the transparent orthography and the agglutinative structure of the language, sublexical processing in reading may be more prominent in Finnish than in many other orthographies (Ziegler et al., 2001; Ziegler et al., 2003b).

The results provided evidence for both the presence and absence of sublexical processing in fluent reading in Finnish. There was a stable 25ms per letter influence on naming response onset times in typical second grade readers, regardless of the words' syllable structures. The number of letters (or phonemes) effect was even stronger in response durations. However, in the lexical decision task there was no consistent number-of-letter effect. On the other hand, a 5ms per letter influence was found on eye fixation durations in silent adult reading in sentence contexts. The fact that the word length effect was present in the naming task and in the fixation durations but not consistently in the lexical decision task allows the possibility that word length effects may be peripheral, that is, stemming from visual input and phonological output processes, as suggested by Seidenberg and Plaut (1998). Visually, a word length effect may result from two distinct processes: from visual acuity constraints as letters farther away from a fixation point suffer from poorer vision relative to letters nearer to a fixation point (Rayner, Reichle, Stroud et al., 2006; Engbert et al., 2005). Second, letters may cause interference with each other's recognition the closer they are to each other (the crowding –phenomena; Bouma, 1970).

The length effect in naming onset response times may be due to articulatory preparation, as the naming response durations clearly show that each phoneme counts when producing an utterance. Counter to this articulatory preparation view, there seems to be no word length effect in picture naming onset response times (Bachoud-Lévi, Dupoux, Cohen & Mehler, 1998), and it is not exceptional to find a null effect of length in written word naming latencies either, irrespective of the orthography studied (Martens & de Jong, 2008; New et al., 2006; Spinelli et al., 2005). Perhaps the decoding process is slightly more activated in the somewhat unfamiliar reading aloud situation relative to the more natural silent lexical decision and picture naming aloud task. After all, we seldom read text aloud but name visual objects quite often in everyday situations.

The word uniqueness point did not affect fluent adults' lexical decision response times, whereas the pseudoword deviation point had a clear impeding influence. This finding provides the most compelling case for the specialized processing of words and pseudowords in the present thesis. Still, even this study leaves open the question of whether the words and nonwords are initially perceived by a shared mechanism and whether the serial processing of nonwords occurs only later when readers try to find a meaning for a novel item. Speculatively, this continued search for meaning may have contributed to the lexicality x number of letters interaction in the naming response duration in typical second grade readers (Bachoud-Lévi et al., 1998; Kello & Plaut, 2003; Hutzler et al., 2005). However, there are also other possible explanations for this finding such as simply the less fluent articulation execution of pseudowords. Taken together, the main finding regarding the number-of-letter effect across the present studies was that fluent readers recognize words with a very small if any influence of number of letters, whereas pseudowords always elicit a strong letter-based effect.

Unlike several other orthographies (Ferrand, 2000; Stenneken et al., 2007; New et al., 2006), there was no sign of an impeding effect of number of syllables in pseudoword (nor in word) reading in typical second grade or adult readers. In fact, similar to small trends for facilitory effects of number of syllables, I found such an effect also in an Italian adult naming latency data, when the number of letters was controlled (Barca, Burani, & Arduino, 2002). I interprete the current evidence to indicate that the role of the syllable in reading is not similar across orthographies, but rather is sensitive to orthography or properties of spoken language. One possibility is that syllable effects are more pronounced in languages having complex syllabification rules and in which the correct syllabification is a necessity for lexical and semantic disambiguation, as is the case in German, Italian and French.

Even though the syllable seems not to be a decoding unit for fluent readers in simple word recognition in certain orthographies, it may nevertheless be an important decoding unit during early reading development in these orthographies. Häikiö (2011) did find a syllable boundary effect on eye movements during the autumn semester in Finnish second-grade children, but not during the spring semester. Moreover, Gagl et al. (2010) found a number-of-syllable effect in the second grade but no longer in the fourth grade in German. Especially in the fully transparent Finnish orthography, syllabic parsing may be a very short period during comparably fast reading acquisition. Finally, there was a facilitative syllable effect in response durations being more pronounced in word than in pseudoword reading, which probably reflects the influence of a long initially stressed syllable on articulation.

Interestingly, the present results suggest that although fluent readers do not use syllables as serial decoding units, they may use the initial syllable of novel words as a lexical search unit for the phonological lexicon. The suggestive evidence for this view is that the pseudoword deviation point effect in lexical decision tasks in fluent readers was located at the syllable boundary. However, the possibility that the effect was produced by a sequence of three initial letters cannot be excluded, as only items on homogenous syllable structure were studied. In any case, it seems reasonable to assume that the initial syllable needs to be sufficiently long in order to be capable of lexical activation. This preliminary observation of the initial syllable possibly having a special role in lexical searches of the phonological lexicon fits nicely with the findings made in another transparent orthography, Spanish, in which the initial syllable frequency effects have been reported numerous times also in real word reading (e.g. Àlvarez et al., 2000; Carreiras et al., 2005). Finally, the initial syllable being a unit for phonological lexical search may explain why the number of syllable effect was found only in lexical decision tasks and not in naming tasks in dysfluent second grade readers, and may explain the documented importance of syllables during early and compromised reading development across orthographies.

3.1.2 Implications for reading models

Next, I will evaluate the suitability of various visual word recognition models for explaining the present pattern of results derived from typical readers in Finnish. First, the missing number-of-syllable effect for pseudowords among typical second grade readers is problematic for the syllable-based models of reading aloud, such as the CDP++ (Perry et al., 2010) and the MTMM (Ans et al., 1998). Both models predict that if the word has no orthographic representation it is subject to serial syllabic processing. Contrary to the CDP++'s prediction, in Study I, there was no sign of serial number-of-syllable effects in skilled reading in Finnish even when reading pseudowords, showing that possible syllabic parsing is not a serial process at least when reading short pseudo/words in Finnish. In MTMM, if the whole word procedure fails to recognize a word, it is read by an analytical procedure. The attentional window of the analytic procedure is very limited for which reason words are read aloud by their subparts, typically as syllable-by-syllable. The only way to accommodate the present results with the MTMM is the possibility that the four to eight letter pseudowords used in the present thesis were within the scope of the attentional window, which is certainly in line with empirical evidence (Häikiö, 2011). Therefore it may be justified to study whether there are syllable effects when reading the long and complex words typical in Finnish: The average word length in a Finnish corpus is 12.5 letters (Kotimaisten kielten tutkimuskeskus, 2007). The fact that typically words fit into perceptual span in reading, however, poses a problem to the MTMM model.

In the CDP models, serial effects result from a left-to-right shift of a visuo-spatial attention. Attention is required for the graphemic parsing producing the number-of-letter effect, and for syllabic parsing producing the number-of-syllable effect. The latter is thought to be necessary for the proper stress alignment of novel words. Taking place after graphemic parsing, the mapping of graphemes to phonemes is a parallel process in this model. The present results are hardly in line with the CDP account of serial effects. First of all, no complex graphemic parsing is required for reading Finnish and yet number-of-letter effects are present in naming latencies. However, the current findings do not exclude the possibility that attention may proceed serially within words for the sake of letter encoding. Generally, progressive refixations are in line with this serial shift of attention. In Study III there was a trend of making refixations according to spatial width, presumably due to reason's of visual acuity. In another earlier study, no evidence of the serial shift of attention was found when the influence of letter order in a word and reading direction in a sentence were orthogonally manipulated (Inhoff et al., 1989). In the present work the effect of the spatial width of a word on single fixation durations was not different from the spatially controlled word length effect, suggesting that the spatial extent of a word per se does not influence word processing time. In conclusion, the available evidence favors the view that the serial shift of attention in word recognition seems to occur only due to limitations of visual acuity, not when recognizing a word fitting within foveal vision.

The DRC model (Coltheart et al., 2001) has been designed only for reading monosyllabic English words and makes no predictions about the number-of-syllable effect. The number-of-letter effect results from the GPC route by serially applying a set of pronunciation rules for a letter string. In Finnish there are very few pronunciation rules, so reading is mainly based on letter-phoneme associations. A GPC route mapping letters to phonemes serially, without graphemic parsing or rule applying, could account for the present findings of the pseudoword length effect in fluent Finnish readers. Further, by speeding up the GPC route, the DRC model has been able to predict stronger serial effects in regular orthographies (Ziegler et al., 2003a). The fine line of finding a word length effect or not may depend on whether the studied individuals possess the orthographic representations of words shown in a particular experiment. Even if there were an equal amount of short and long items not having solid memory representation, the result in the DRC is a small word length effect as longer items take longer to read by the serial reading procedure. To avoid this problem, instead of relying on frequency corpuses, one could test beforehand which words the subject is familiar with. The possibility that the initial syllable or the sequence of initial phonemes has a special role in lexical searches of the phonological lexicon also requires a modification of the DRC model. The easiest solution to this would be that the phonemic assembly is fed in syllables or phonemic segments, not in individual phonemes, into phonological lexicon.

The Strong Phonological Theory of Reading (SPT; Frost, 1998) states that phonological decoding typically precedes lexical access to the phonological lexicon, although for the most common words, a visual iconic representation may exist. The present results indicate that at least such a phonological decoding is not entirely serial and letter-based as already in the second grade children responded at equal speed to bisyllabic four-letter *(ka-na)* and trisyllabic six-letter *(ki-ta-ra)* words in the lexical decision task. However, both the findings of the facilitative effect of number of syllables in Study II and the word length effect in fixation duration in Study III can be interpreted as caused by the consonant-vowel complexity of the words, which is line with the SPT's view that such rapid phonological coding may be consonant-driven, and perhaps conducted via parallel letter processing. As will be discussed, the SPT also provides a suitable account for results obtained with dysfluent readers.

Finally, it must be highlighted that state-of-the art connectionist models having the capability of sequential processing are also relevant options for interpreting the present pattern of results. The most recent model (Sibley, Kello, & Seidenberg, 2010) is capable of producing a lexicality x number of letter effect by applying distributed memory representations of words, and by producing a phonological code for pseudowords by taking advantage of the sublexical predictability in a language. Such a solution would also work in transparent orthographies where mapping from orthography to phonology may be straightforward but where readers are nonetheless sensitive to graphotactical patterns of their language. For example, in Finnish there are lots of words sharing the same ending, such as 'mustikka' (blueberry) and 'mansikka' (strawberry), so a pseudoword such as 'sirpikka' would certainly be easy to read by natives. Certainly, this explanation is appealing for interpreting the present uniqueness and deviation point findings: Real words gain from memory representations (distributed) resulting in no serial effect whereas when reading pseudowords readers try to make use of their existing associations activated by the word beginning. For explaining the substantial serial effects typically found in pseudoword reading, this predictive serial generation of phonological code (Sibley et al., 2010) seems to me a more plausible explanation than the serial visual input scheme (Plaut, 1999; Sibley et al., 2010).

In connectionist approaches, the idea that some words are phonologically decoded whereas some words are recognized without phonological decoding, has been lately termed as division-of-labor (DoL) (Harm & Seidenberg, 2004). The straight route from orthography to meaning is especially useful in English where some words cannot be phonologically decoded, whereas the relevancy of this pathway for reading in fully transparent orthographies, in which all words can be phonologically decoded, may be smaller, as suggested by the orthographic depth hypothesis (Katz & Frost, 1992; Lukatela et al., 1980, 1989).

While word recognition theories have been mainly concerned with the mapping between graphemes and phonemes, theories of the eye movement control in reading have modeled reading behavior in connected text. Sharing partially common questions, surprisingly little work aiming at theoretical integration between these two approaches has taken place. In the present thesis the critical word length effect was studied in a silent sentence reading task and the results were discussed both in the light of word recognition and eye movement control theories. Specifically, the word recognition theories (such as the DRC) predicts the number-of-letter effect resulting from linguistic processing, whereas the eye movement theories (E-Z-reader, SWIFT) predict the word length effect stemming from visual processing, as in these models the time required for letter encoding is thought to be dependent on the distance of the letter from a fixation point. Therefore, the spatial width, not the number of letters, would be responsible for the temporal word length effect. The present results of uniform word length effect in fixation durations irrespective of whether the spatial width was controlled or not provide support for the linguistic explanation. However, as already mentioned, another visual process called visual crowding (Bouma, 1970), which is the amount of visual interference produced by nearby objects, may be responsible for the spatially controlled word length effect. On the other hand, the number-of-letter effect was only present when fixating on the word and not during the preceding fixation on the previous word, which suggests that direct visual attention is a prerequisite for the temporal number-of-letter effect. However, as visual crowding is known to be stronger in parafoveal and peripheral vision than in foveal vision, it is a little surprising that the dense six-letter proportional font words did not receive any longer preview fixations. Instead, phonological decoding is believed to require more direct attention than the whole-word recognition (Reynolds & Besner, 2006), so it seems likely that the temporal word length effect reflects a genuine decoding process instead of visual crowding, which should exert its influence also on the parafoveal preview fixation. However, although I think that attention is required for the serial mapping and assembly process, I believe that a serial shift of attention is required only when the word extends beyond foveal vision. As already said, this view was supported by the trend in refixations when the spatial width was increased along the number of letters.

3.2 Dysfluent reading in Finnish

3.2.1 Discussion of empirical findings

Dysfluent reading in Finnish children, as in other regular languages (Zoccolotti et al., 2008; Di Filippo et al., 2006; Juphard et al., 2004; Martens & de Jong, 2006), was characterized by larger responses to lexicality and length manipulations in naming and lexical decision tasks when compared to peers matched by age and general cognitive ability. The eye movement recordings further revealed that the dysfluent readers processed the words in a similarly fragmented manner as the pseudowords (De Luca et al., 2002; De Luca et al., 1999; Hutzler & Wimmer, 2004) and could not shift to a more holistic processing style with the aid of repetition. However, as studied by using the orthographic uniqueness and deviation points, adult dysfluent readers were capable of slightly slower whole-word recognition and orthographic processing, but still had difficulties with pseudoword recognition, suggesting a phonological locus of their reading difficulties.

The separation of response onset time and response duration revealed that the dysfluent second grade readers relied on the online phonological decoding strategy by sliding through the items almost phoneme-by-phoneme without first assembling them all together. In contrast, the typical readers relied on this strategy to a substantially lesser degree. As the naming data reported from other transparent orthographies (e.g. from Italy; De Luca et al., 2009) have not shown any signs of this strategy, the completely transparent orthography may only be a prerequisite, but not the cause for this decoding strategy. It may be that the Finnish reading education system has equipped the children with this strategy, as children are systematically taught to decode online (Lerkkanen, 2007).

In lexical decision tasks, where lexical access is required, the poor readers showed generally delayed response times and a number-of-syllable effect on both words and pseudowords. Thus, when complete word recognition is required, poor readers seem to parse the phonemes into syllables. However, there were only weak signs of this syllabic parsing of pseudowords in the naming task. It may be that the poor readers' attention in reading aloud is mainly concerned with the fast production of correct phonemic articulation, while the an effortful recognition of the identity of the word and understanding its meaning takes place later, even post-response. If this is the case, the response onset and duration measures of the naming task would not be able to capture the entire process, but only the decoding part of the poor readers' visual word recognition process.

3.2.2 Implications for poor reading

Generally, dyslexia is thought to result from problems in phonological processing or in the connectivity between orthographic and phonological processing (Rayner et al., 2001; Vellutino et al., 2004). Thus, the CDP+'s view that the word length effect results from a left-to-right shift of attention, and dyslexia from a deficit in this attention mechanism, is clearly an alternative to the phonological deficit view. As eye movement data show (De Luca et al., 2002; De Luca et al., 1999; Trauzettel-Klosinski et al., 2009) dyslexics do proceed serially within words, but according to the phonological view this is due to problems in decoding, not in attention. Also, the CDP++ model does not predict a role for the syllabic parsing in lexical access, but in the stress alignment of naming responses, unfitting also in this respect to the present data. The MTMM predicts developmental dyslexia resulting from deficient whole-word recognition and a reduced attentional window of the analytic decoding process leading to letter-by-letter or syllable-by-syllable reading. The present results would fit this model only if, for some unknown reason, dysfluent readers would decode words letter-by-letter in naming tasks, and additionally syllable-by-syllable in lexical decision tasks. Given the generally delayed response times and high influence of the number of letters in lexical decision tasks, it seems more likely that the syllable effect is a sign of some additional process taking place after the letter-by-letter decoding. As the initial syllable was found to be a lexical access unit even for fluent Finnish readers, a more plausible idea seems to be that parsing the phonemes into syllables does help the poor readers to attain phonological lexical access.

Instead of the alternative explanations, the general dual-route architecture with deficiencies in both GPC and whole-word recognition (Bergmann & Wimmer, 2008) or SPT's view of phonological lexical recognition provides a good framework for understanding the present results derived from poorly reading Finnish children. Apparently, the hypothesized orthographic route has not been established yet at the fifth grade as revealed by the extensive number of fixations made on the words. The poor readers' visual word recognition is essentially based on letter-phoneme decoding, as shown by the dominant number-of-letter effect. In addition, assembling phonemes together seems to be a major challenge for struggling readers. When lexical access was required in the lexical decision task, dysfluent readers were more impaired than in naming and they also assembled the phonemes into intermediate units, syllables. This pattern of results may indicate that deficient phonological processing interferes also with lexical access. In addition, with adult dysfluent readers, the present results suggest that eventually a functional but slow whole-word recognition is established, whereas the problems in phonological decoding seem to remain in young adulthood. According to SPT, a mere phonemic code may not be sufficient for phonological lexical access, but that other phonological properties, such as the syllabic parsing for stress alignment may also be required for activating the correct phonological lexical representation. Alternatively, a connectionist explanation would be that deficient phonological processing (e.g.

poor grapheme-phoneme associations and phonemic assembly) impairs semantic activation (Harm & Seidenberg, 2004). Therefore, I suggest that it would be important to study whether Finnish dyslexics have problems in activating semantic information from print, and if so, what practices would promote reading for meaning.

3.3 Limitations and methodological issues

The issue of data quality was taken into account when designing the experiments for children, and when processing the data (Study I). For lessening data accuracy and precision demands, a maximum of two rows of text were simultaneously presented, small font sizes were avoided and a double space was assigned between the words. Eye movement data processing includes saccade and fixation detection, area-of-interest (AOI) analysis and calculation of dependent variables. Challengingly, poor readers make short intra-word saccades resulting in low peak saccade velocities. In the present thesis the value was determined by a visual inspection of data samples. More data-based solutions such as the one suggested by Nyström and Holmqvist (2010) would be an improvement. One major challenge was to calculate the AOI analysis and the dependent variables by SPSS programming. Currently, thanks to the manufacturer's software updates, our eye tracking system has fully integrated stimulus presentation and analysis software, including an automatized data analysis package for reading studies. Therefore, conducting an eye tracking experiment is currently relatively easy. With short laboratory training concentrating on measurement skills, the methodology can be exploited by even undergraduate students, as has already been accomplished. Such training should include subject handling, eye video and tracking parameter adjustments with and without eye glasses or lenses, and calibration.

Finally, the present thesis contains some limitations that need to be mentioned. First of all, the present studies provide only "snapshots" about reading development, and therefore give an insufficient picture, especially about early reading development in Finnish. For capturing the rapid reading acquisition of Finnish children, a selective week-by-week follow-up from preschool- to the third grade would be required (Aro, 2004). An intensive research effort including eye tracking and brain research of word recognition should focus on the time period when a child is starting to master the alphabetic principle and will be soon learning to decode and recognize words onwards. Additional challenges in such a study would be the presentation of a sufficiently large amount of age-appropriate items while avoiding repetition effects. A second limitation is that all the present results apply only to the visual word recognition of simple nouns in their nominal form. This was an intentional choice as the natural reading of morphologically complex words is extensively studied at the University of Turku by Dr. Hyönä and colleagues, while the recognition of simple words in Finnish has been a neglected topic despite the fully transparent orthography and despite the fact that developmental dyslexics also show deficiencies in single word recognition. That said, a topic for future research would be to study how poorly and typically developing children learn to read morphologically complex words. The positive aspect of the present research is the versatile, critical and in-depth approach to serial processing in visual word recognition and dyslexia. It contains a brand new innovation for dissociating spatial width from number of letters, and exploring the idea of the word uniqueness point for the first time in the context of a transparent orthography.

TIIVISTELMÄ

Visuaalinen sanantunnistus sujuvilla ja hitailla lukijoilla kirjain-äänne vastaavuudeltaan läpinäkyvässä suomen kielessä

Kirjoitusjärjestelmältään epäsäännönmukaisessa Englannin kielessä kehitettyjen kirjoitettujen sanojen tunnistamisen mallit koostuvat yleensä kahdesta erillisestä prosessista: sarjallisesta kirjaimittain ääntämystä tuottavasta sekä yhtäaikaisesti sanan kaikkia kirjaimia käsittelevästä, muistijälkeen perustuvasta tunnistamisesta. Lukemisen pulmat nähdään kehityksellisenä vaikeutena saavuttaa jälkimmäistä prosessia, jolloin lukeminen tapahtuu hitaamman sarjallisen prosessin varassa. Myös sarjallisen prosessin epäillään toimivan hitaammin lukivaikeudesta kärsivillä henkilöillä.

Tämä väitöskirja pyrki selvittämään ensinnäkin miten yksinkertaisia kirjoitettuja sanoja tunnistetaan suomen kielessä, jossa säännönmukaisen kirjoitusjärjestelmän vuoksi lukeminen voi periaatteessa perustua täysin sarjalliseen prosessiin, ja toiseksi, miten hitaasti lukevien lasten ja aikuisten sanantunnistus eroaa sujuvista lukijoista. Keskeisenä kysymyksenä on mitkä ovat lukemisen perusyksiköitä (kirjaimet, tavut, sanat) sujuvassa ja hitaassa lukemisessa.

Ensimmäisessä osatutkimuksessa verrattiin hitaita kouluikäisiä lukijoita sujuviin aikuisiin lukijoihin kun tehtävänä oli lukea ääneen toistuvia sanoja ja epäsanoja. Epä/sanojen kirjainten ja tavujen lukumäärää käsiteltiin toisistaan riippumatta. Lukemisen aikaiset silmänliikkeet taltioitiin ja analysoitiin. Tulokset osoittivat hitaiden lapsilukijoiden tekevän sujuvia aikuisia enemmän silmän fiksaatioita kirjainta kohden. Aikuisilla kirjaimilla oli pienempi vaikutus fiksaatioiden lukumäärään luettaessa sanoja kuin epäsanoja, kun taas lapsilla fiksaatioita lisättyä kirjainta kohden tehtiin yhtä paljon luettaessa sanoja ja epäsanoja. Toisto vähensi fiksaatioita kirjainta kohden aikuisilla, mutta ei heikoilla lukijoilla. Tavumanipulaatio ei tuottanut selkeitä löydöksiä. Tulokset tukevat näkemystä että kun sujuvat lukijat pystyvät muodostamaan nopeasti uusia sanaedustuksia, hitaat lukijat tukeutuvat lähinnä sarjalliseen prosessointiin, eivätkä näytä pystyvän tunnistamaan sanoja kokonaisina toistostakaan huolimatta.

Toisessa osatutkimuksessa verrattiin tavallisia ja hitaasti lukevia kakkosluokkalaisia kirjoitettujen sanojen nimeämisessä sekä leksikaalisen päätöksenteon tehtävässä, jossa tehtävänä on päättää onko kirjainjono sana vai ei. Jälleen epä/sanojen kirjain- ja tavumäärää muunneltiin toisistaan riippumatta. Tavallisesti lukevat lapset näyttivät lukevan epäsanoja kirjaimittain kun taas sanojen lukemisessa kirjain- ja tavumäärillä oli vain pieniä, vaikeasti tulkittavia vaikutuksia. Heikoilla lukijoilla kirjainmäärä vaikutti voimakkaasti reaktioaikoihin niin epäsanoja kuin sanojakin luettaessa. Myös nimeämisen kestot olivat heillä paljon pidempiä heijastellen kirjainjonojen vaikeutta, mikä viittaa siihen että heikot lukijat tuottavat ääntämystä lähes kirjain-kirjaimelta, etenkin kun sanat ovat heille vieraita. Lisäksi kun tehtävänä oli päättää onko kirjainjono sana vai epäsana, suurempi tavumäärä hidasti reaktioaikoja. Tämä saattaa johtua siitä

että heikot lukijat kokoavat yksittäiset äänteet ensin tavuiksi, ja edelleen tavut kokonaiseksi sanaksi.

Kolmannessa osatutkimuksessa syvennyttiin sanan pituusvaikutuksen kahteen mahdolliseen osatekijään, sanan kirjainten määrään ja sanan leveyteen, joita aikaisemmassa tutkimuksessa ei ole kyetty luonnollisin keinoin erottamaan. Hyödyntämällä kirjainten vaihtelevia leveyksiä voidaan löytää sanoja jotka ovat yhtä leveitä mutta sisältävät eri määrän kirjaimia. Tällaista leveydeltään kontrolloitua kirjainmäärän vaikutusta verrattiin perinteiseen pituusvaikutukseen, jossa kirjainmäärä ja leveys ovat kytkeytyneet toisiinsa. Erimäärän kirjaimia sisältävät kohdesanat olivat upotettuja identtisiin lauseisiin, joiden lukemisen aikaiset silmänliikkeet rekisteröitiin. Löysimme leveydestä riippumattoman kirjainmäärän vaikutuksen sanaan kohdistuneiden fiksaatioiden kestoihin, mikä saattaa johtua joko kirjainten lukumäärästä, tai vaihtoehtoisesti kahdesta visuaalisesta prosessista, näön tarkkuuden rajoituksista leveämpien sanojen tunnistamiselle tai lähekkäin olevien kirjainten näölle aiheuttamasta kuormituksesta, ns. ruuhkautumisesta. Sen sijaan silmänliikkeet, sakkadit, olivat täysin määräytyneitä sanan leveyden mukaan, sisältäen päätöksen hypätäänkö sana yli vai ei, ja tehdäänkö sanaan toinen fiksaatio vai ei.

Neljännessä osatutkimuksessa tutkittiin eteneekö sujuvien ja hitaiden aikuisten lukijoiden sanaedustuksen muistista haku sarjallisesti (kirjaimittain), vai vaikuttavatko kaikki kirjaimet yhtäaikaisesti tähän hakuun. Tätä kysymystä voidaan tutkia sanan yksilöitymispisteen avulla, eli laskemalla sanan alusta se kirjain, jossa yhdelläkään toisella sanalla ei ole enää samaa alkua. Esimerkiksi sanalla 'KISSA':n yksilöitymispiste on kolme, koska mikään muu viisikirjaiminen sana ei ala tavulla 'KIS'. Sen sijaan sanalla 'TAKKI' yksilöitymispiste on myöhäisempi viisi koska on olemassa sana kuten 'TAKKA'. Pseudosanojen kohdalla samaa asiaa nimitetään sanasta eroamispisteeksi. Kaksoisreittimallin mukaisesti oikeiden sanojen lukemisessa yksilöitymispisteellä ei ollut vaikutusta sanan tunnistamisnopeuteen leksikaalisen päätöksenteon tehtävässä, kun taas pseudosanojen kohdalla yksilöitymispisteellä oli vahva hidastava vaikutus reaktioaikoihin. Tämä vaikutus syntyi kun ensimmäinen tavu sopii oikeaan sanaan, mikä viittaa siihen että tavu on tärkeä yksikkö myös sujuvilla lukijoilla haettaessa mielestä sanoja sarjallista lukustrategiaa käytettäessä. Hitaat lukijat reagoivat poikkeavan hitaasti vain pseudosanoihin, mikä viittaa ongelmiin fonologisessa prosessoinnissa. Sen sijaan myös hitaat lukijat näyttävät kykenevän hiukan hitaammin toimivaan kokosanatunnistukseen.

Yhteenvetona kirjain-äänne vastaavuudeltaan säännönmukaisessa suomen kielessä lyhyiden sanojen kirjaimia käsitellään yhtäaikaisesta, mutta myös sanan visuaalisilla piirteillä tai sanan rakenteella saattaa olla pieni, tässä tutkimuksessa epäselväksi jäävä rooli. Vieraiden sanojen lukeminen perustuu sen sijaan sarjalliseen mekanismiin, jossa ensimmäisellä tavulla saattaa olla erityinen merkitys sanaedustusten aktivoinnissa. Hitaasti lukevien lasten sanantunnistus näyttää perustuvan pääasiassa sarjalliseen lukustrategiaan, kun taas aikuisten hitaiden lukijoiden sanantunnistus näyttäisi olevan vain yleisesti hitaampaa. Ainakin vielä kakkosluokalla hitaasti lukevat lapset näyttävät etenevän lähes äänteittäin ja kun heitä vaaditaan ymmärtämään lukemansa sana, he ovat erityisen hitaita ja näyttävät kokoavan äänteet tavuiksi. Nämä löydökset herättävätkin kysymyksen häiritsevätkö dekoodauksen pulmat hitaita lukijoita tavoittamaan sanan merkitystä, ja auttaako heitä siinä äänteiden yhdistäminen tavuiksi.

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ORIGINAL PAPERS

I

Sublexical effects on eye movements during repeated reading of words and pseudowords in Finnish

by

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SUBLEXICAL EFFECTS ON EYE MOVEMENTS DURING REPEATED READING OF WORDS AND PSEUDOWORDS IN FINNISH

The role of different orthographic units (letters, syllables, words) in reading of orthographically transparent Finnish language was studied by independently manipulating the number of letters (NoL) and syllables (NoS) in words and pseudowords and by recording eye movements during repeated reading aloud of these items. Fluent adult readers showed evidence for using larger orthographic units in (pseudo)word recoding, whereas dysfluent children seem to be stuck in a letter-based decoding strategy, as lexicality and item repetition decreased the NoL effect only among adult readers. The NoS manipulation produced weak repetition effects in both groups. However, dysfluent children showed evidence for word-specific knowledge by making fewer fixations on words than pseudowords; moreover, repetition effects were more noticeable for words than pseudowords, as indexed by shortened average fixation durations on words due to item repetition. The number of fixations was generally reduced by repetition among dysfluent children, suggesting familiarity-based benefits perhaps at the perceptual level of processing.

Key words: eye movements, word recognition, word length, number of syllables, reading ability

Introduction

When learning to read one first has to break the orthographic code. Languages differ in how complex the mapping is between the written and spoken language. In its simplest form each letter corresponds to a unique phoneme and vice versa. In these kinds of transparent orthographies (e.g. Finnish), learning to read is greatly facilitated when compared to more opaque orthographies such as English (Seymour, Aro, & Erskine, 2003). Naturally, even in transparent orthographies the mapping

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must be automatized to attain a fluent reading skill (LaBerge & Samuels, 1974). This automatization is well captured by decoding speed (Ehri & Robbins, 1991; Marsh, Friedman, Desberg & Saterdahl, 1981a; Marsh, Friedman, Welsch & Desberg, 1981b; Tunmer & Hoover, 1993), i.e. the rate at which one can translate letters and words into speech when reading aloud. This efficiency in turn contributes to the experienced pleasure of reading rather than mere recognition accuracy (Leinonen et al., 2001). One strategy to improve reading fluency is to read the same words or texts several times (Laberge & Samuels, 1974), with even a few repetitions producing marked improvement in reading speed (Hyönä & Niemi, 1990; Reitsma, 1983; Share, 2004, for a review, see Ehri, 2005). Repeated reading is also used to remediate reading fluency among dyslexics (Chard, Vaughn, & Tyler, 2002). However, it is not clear which reading processes are affected by repetition and which orthographic units (e.g. syllables or words) should be repeated. The latter question is especially relevant when seeking efficient ways to promote reading fluency especially among struggling readers.

Dual-route theories (e.g. Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) suggest that words can be recognized either by an analytic letter-to-phoneme conversion or via a whole-word route. In the former strategy, the reader breaks down the word into individual letters or groups of letters, thus allowing access to corresponding phonemic representations. Then these phonemic representations are combined and a phonological representation of the word is accessed. In order to use the latter strategy, the reader must have developed word-specific orthographic representations, and little, if any, phonological processing would be required to access the word identity. In general, sublexical factors are more important when reading pseudowords or infrequent words as compared to reading frequent words – a pattern of results supporting the dual-route view of word decoding.

The dual-route theory is mainly based on data on reading simple monosyllabic words. In many languages, long and complex words are common, containing complex consonant clusters and/or multiple syllables and morphemes. It seems plausible to assume that even in fluent reading these types of words are not recognized as whole words but via smaller units. Thus, the recognition units in reading may be viewed as a continuum from small-size letter/phonemic units via multi-letter units to complete words (Duncan, Seymour, & Hill, 2000; Thaler et al., 2009). It is known that dyslexics are highly affected by sublexical factors, possibly because they have problems in forming or retrieving larger orthographic representations and thus have to rely on a sublexical reading strategy (Zoccolotti, De Luca, Di Pace, Judica, & Spinelli, 2005). For these readers, repeated reading may thus improve reading speed by supporting the formation of larger orthographic representations.

The present study was conducted to gain more insight into fluent and dysfluent word decoding by studying the independent effects of the number of letters (NoL) and number of syllables (NoS) during repeated reading of words and pseudowords. Eye fixation patterns on words and pseudowords were used as online indices of decoding fluency during reading aloud. The reading-aloud task was selected to ensure that the readers engaged in proper decoding of the target items. The NoL effect, commonly termed as the word length effect, provides an indicator of small-unit decoding, whereas the NoS effect, or the syllabic length effect as termed by Ferrand (2000), indicates a possible contribution of larger-unit processing. Repeated reading provides a dynamic window to the use of sublexical units: sublexical effects should diminish as words or pseudowords become increasingly familiar due to repetition. It was expected that fluent adult readers are able to rapidly form new orthographic representations as indexed by a significant reduction in NoL and NoS effects in the pseudoword condition. On the other hand, as hypothesized above, dysfluent child readers may be unable to quickly acquire new orthographic representations, and thus no reduction in sublexical effects was expected.

Using the eye tracking methodology, we were in a position to obtain detailed information about how the studied effects manifest in on-line processing of words and pseudowords. During reading the eyes make stationary stops (fixations) lasting a few hundred milliseconds, during which visual information is acquired. Between fixations the eyes make rapid movements called saccades, during which vision is greatly suppressed. The number of fixations made on a word or pseudoword indicates if the lexical item is recognized instantly during a single fixation or whether recognition is spilled across several fixations (see Rayner, 1998 for a review of eye movements in reading). Hawelka, Gagl and Wimmer (2010) have recently provided an excellent account of how eye movement measures may be understood from the dual-route perspective of reading. Essentially, if several fixations are made on a single word during its initial encounter, a sublexical unit, instead of the whole word, may be recognized during each fixation. If this is the case, a connection between the number of sublexical units and the number of fixations would be found. With respect to item repetition, a reduced number of fixations due to repetition would indicate a shift to more parallel processing, whereas a decrease in average fixation duration would imply an increase in processing efficiency (Reichle, Vanyukov, Laurent, & Warren, 2008). Finally, familiar stimuli may receive fewer and shorter fixations than infrequently encountered stimuli. Nazir et al. (2004) and Maloney et al. (2009) have suggested that this kind of familiarity effect may be non-linguistic in nature and related to perceptual processes.

Letters are self-evident small-size units of reading and necessarily decoded during the course of word recognition. The amount of processing devoted to each letter in a word is captured by the word length (in letters) effect. If words are recognized solely by the whole-word strategy, no word length effect should be observed. In line with the dual-route theory, the pseudoword length effect is demonstrated to be much stronger than the word length effect, which may even be absent in the word naming latencies among adult readers (De Luca et al., 2002; Frederiksen & Kroll, 1976; Martens & De Jong, 2008; Weekes, 1997; Ziegler, Perry, Jacobs, & Braun, 2001). More commonly however, also adult readers show a small but nonetheless reliable word length effect, as reviewed by New, Ferrand, Pallier and Brysbaert (2006). The word length effect has also been apparent in readers' eye movement (Calvo & Meseguer, 2002; Bertram & Hyönä, 2003; De Luca et al., 2002; Hutzler & Wimmer, 2003; Hyönä & Olson, 1995; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004; MacKeben et al., 2004; Rayner, Sereno, & Raney, 1996, but see Joseph, Liversedge, Blythe, White, & Rayner, 2009). The effect among fluent readers is mainly caused by increased refixations on longer words, but also to some degree by increased fixation durations on words read by a single fixation.

Developmentally, a substantial decrement in the word length effect is seen during the early school years (Martens & de Jong, 2006; 2008; Spinelli, De Luca, Mancini, Martelli, & Zoccolotti, 2005; Zoccolotti et al., 2005). On the other hand, a prolonged word length effect is the most striking behavioral manifestation of dyslexia, presumably indicating the continued use of a letter-by-letter reading strategy (De Luca et al., 1999, 2002; Hutzler & Wimmer, 2003; Zoccolotti et al., 2005; Martens & De Jong, 2006a, 2008; Thaler et al., 2009). In the aforementioned eye movement studies, the length effect among beginning and dyslexic readers is also seen in fixation frequency measures, providing strong evidence for the use of small recognition units in reading.

There is also some evidence for the role of sublexical units larger than letters in word decoding. In irregular orthographies recognition of specific letter combinations is motivated by the unique pronunciation they may code (Paap, Noel, & Johansen, 1992; Rastle & Coltheart, 1999). For example, in German there is evidence for consonant clusters working as perceptual units (Marinus & de Jong, 2008; Thaler et al., 2009). In many languages, words are formed as combinations of a relatively limited number of syllables. An effect of the number of syllables in naming and lexical decision latencies for visually presented words has been shown in English (an irregular but not syllable-stressed language; Jared & Seidenberg, 1993; New et al., 2006), in French (an irregular and syllable-stressed language; Ferrand, 2000; Ferrand & New, 2003), and in German (a regular but not syllable-stressed language; Stenneken, 2007). Additional support for the involvement of syllables in reading comes from syllable frequency studies conducted in Spanish (Álvarez, Carreiras, & Perea, 2004), German (Hutzler, Conrad, & Jacobs, 2005), and English (Macizo & Van Petten, 2007; Ashby & Rayner, 2004).

Finnish – the language of the present study – has a perfect one-to-one mapping between letters and phonemes, enabling an excellent opportunity, particularly for poorer readers, to make use of the letter-by-letter decoding strategy. In fact, there is evidence that word length effects are particularly pronounced in transparent orthographies (Ziegler et al, 2001). Also the syllable seems like a suitable sublexical unit in Finnish, as syllables are salient units in spoken Finnish, with the initial syllable of a word always being stressed (Suomi, Toivanen, & Ylitalo, 2002). Syllabification is traditionally explicitly taught in early reading education, e.g. hyphens are inserted at syllable boundaries in first-grade ABC books, and a common instructional approach is to read words aloud syllable by syllable. Finnish syllables consist of one to four letters and are only approx. 3000 in number. Because of inflectional and agglutinative morphology, words have numerous forms; word compounding is also very productive. For these reasons Finnish words are typically long. Due to restrictions of visual acuity (the foveal vision extends about 2 degrees of visual angle) Finnish words often require multiple eye fixations to be successfully identified (see e.g. Bertram & Hyönä, 2003). Thus, it seems plausible to think that even in fluent decoding of Finnish sublexical units are in use.

To date, only few studies have examined sublexical effects during repeated reading. Martens and de Jong (2008) studied the effect of repetition in a naming task with reference to word length (number of letters) and lexical status (word or non-word) in Dutch. They found that the magnitude of the lexicality effect was reliably decreased by repetition. There was a reduction in the length effect in absolute values, but the reduction was found to be proportional to the improvement in overall reading speed, and therefore it was concluded that the relative influence of the word length remained similar across repetitions. The reduction in the lexicality effect was similar for dyslexics, chronological age- and reading age-matched controls. The chronological age-matched controls, surprisingly, did not show even a pseudoword length effect, thus preventing a repetition effect from manifesting itself. Judica, de Luca, Spinelli and Zoccolotti (2002) did not find reduction in the length effect among dyslexic readers after extensive practice with rapid presentation times, while Hayes, Masterson and Roberts's (2004) case study demonstrated a reduction in the length effect in a dyslexic subject. Finally, Katz et al. (2005) showed that a sublexical regularity effect (the difference in response latency between words with regular versus irregular spelling-sound correspondences) could be cancelled by repetition in the lexical decision task but not in the naming task where pronunciation was required.

A couple of eye movement studies have examined the effects of repeated reading among adult readers. Hyönä and Niemi (1990) studied repeated reading of a single text and found a general facilitation effect due to repeated reading, which was reflected in a decrease in the summed fixation time, average fixation duration, the number of progressive and regressive fixations, as well as in an increase in average saccade length. Raney and Rayner (1995) demonstrated that rereading had a uniform effect for reading high and low frequency words, suggesting that repetition may exert a general facilitatory effect on word recognition so that few repetitions are not sufficient to cancel out the frequency effect.

A handful of studies has examined if repetition effects generalize to reading of non-repeated items containing the same sublexical parts with the practiced ones. Reitsma (1983) found that repeated articulation of words produces a transfer effect generalizing to homophone spellings, suggesting a phonological locus of the training. Berends and Reitsma (2006) demonstrated a generalization of training effect to orthographic neighbor words only when the training had an orthographic locus (a semantic task did not produce a generalized training effect). In a series of studies, Huemer and her colleagues trained children to read syllables (Huemer, Aro, Landerl, & Lyytinen, 2010) and onset consonant clusters (Huemer, Landerl, Aro, & Lyytinen, 2008) and obtained transfer to reading of words and pseudowords containing these trained units. These studies are encouraging with regard to the hypothesis that learning to recognize larger sublexical units might promote reading fluency in dysfluent readers.

The present study was conducted to investigate the extent to which different sublexical units are utilized in reading among fluent adults and dysfluent children and whether it is possible to enlarge the recognition units by repeated reading. Participants read aloud word and pseudoword lists repeatedly ten times from a computer screen while their eye movements were tracked. To study NoL effects, bisyllabic items of 4, 6 and 8 letters were used. Based on previous studies, dysfluent child readers were expected to show a NoL effect for both pseudowords and words with no effect of repetition, whereas adults were expected to show mainly a pseudoword length effect with a rapid decrement in the effect size due to repetition. To study NoS effects, 8–letter items containing 2, 3 or 4 syllables were presented. Based on previous studies (Stenneken, 2007; Ferrand, 2000; Ferrand & New, 2003), a NoS effect was expected to be found for adults, whereas dysfluent children were not likely to demonstrate NoS effects even after repeated exposure, since they seem to rely on relatively persistent letter-by-letter reading (Thaler et al., 2009).

Method

Participants

The group of fluent adult readers consisted of nineteen participants with a mean age of 29.4 years (SD = 6.6). Two adult participants were excluded from the analysis due to their slow performance in a text reading-aloud task (156 s and 143 s, when group M = 119 s and SD = 13.6) presented before the experiment. The eighteen dysfluent child readers were volunteers from a concomitant training study with a mean age of 10.5 years (SD = 11 months). The children's reading level was at least 1 z-score (M = -1.56, SD = 0.511) below their age-level norms in a standardized reading task (LUKILASSE; Häyrinen, Serenius-Sirve, & Korkman, 1999), while performing at the normal level in a general intelligence test, RAVEN M = 30.39, SD = 2.89. All the children followed the normal curriculum in regular classrooms.

Apparatus

Eye movements were recorded by a SMI HiSpeed eye tracker with a 500 Hz sampling rate. Participants were comfortably seated in a solid chair in front of a height-adjustable table, their foreheads resting on the eye tracking apparatus attached to the table. A 13-point calibration procedure was carried out before the experiment. Participants' speech during the experiment was recorded by a PC.

Materials

The stimulus materials consisted of 10 phonotactically legal pseudowords and 10 basic form words, either nouns or adjectives. Each item was repeated ten times in different locations on two text lines. There were five types of words/pseudowords matched for word and bigram frequency: CV.CV = 4L (letters) 2S (syllables), CVC.CVC = 6L2S, CVVC.CVVC = 8L2S, CV.CVC.CVC = 8L3S, CV.CV.CV.CV = 8L4S.

The set of 4L2S, 6L2S and 8L2S items was used to examine the word length effect independent of the number of syllables, which was held constant (i.e. two syllables). The set of 8L2S, 8L3S and 8L4S items was used to study the effect of the number of syllables independent of word length, which was held constant (i.e. eight letters). Pseudowords and real words were presented in separate blocks so that the pseudoword block was read before the real word block.

Procedure

The computer screen was located at a distance of 66 cm from the participant's eyes. The stimulus items were displayed on two lines in Courier New 18 pt font, in which one letter corresponded to 0.43° of visual angle. Prior to the presentation of each stimulus screen, a fixation cross appeared at the beginning of the first text line. The first word on both text lines was a filler word not included in the data analyses. The inclusion of these filler words was done to exclude noisier data in the eye movement record due to stimulus appearance (the first word of the upper text line) and return sweeps (the first word of the second text line). Participants were instructed to read aloud all the words on the screen as fast and accurately as they could. The experimenter manually controlled the appearance and disappearance of the stimulus screens contingent on the participant's gaze and reading aloud. The experiment lasted approximately 15 min.

Eye movement data handling

Raw eye data were parsed into fixations and saccades by SMI's velocity based detection algorithm using a peak velocity threshold of 30 °/s. Periods of unstable data or inaccurate calibration were coded manually and excluded from the analysis. Only fixations longer than 50 ms were included in the analysis. Each stimulus item served as an area of interest. Fixations were assigned to these areas of interest, and the eye movement measures were averaged for each stimulus category. Values deviating more than 3 SD from the condition average were replaced by the value of M + 3 SD. This correction was made separately for each dependent variable. The ten repetitions were split into two halves by averaging the first five repetitions into block 1 and the last five repetitions into block 2.

Statistical analyses

Repeated measures ANOVAs were performed on the data using a 2 (group) x 2 (block) x 2 (lexicality) x 3 (number of letters or number of syllables) design (the last three variables were within-participants variables). The following dependent variables were used: gaze duration (i.e. the time spent fixating a stimulus item during its initial encounter, i.e. first-pass reading), the number of first-pass fixations, and average fixation duration during first-pass reading. The gaze duration reflects overall processing time of the item. The fixation frequency measure reveals whether a letter string can be processed during a single fixation or whether a refixation is needed to complete its recognition. Average fixation duration indexes the relative ease of processing during individual fixations.

Results

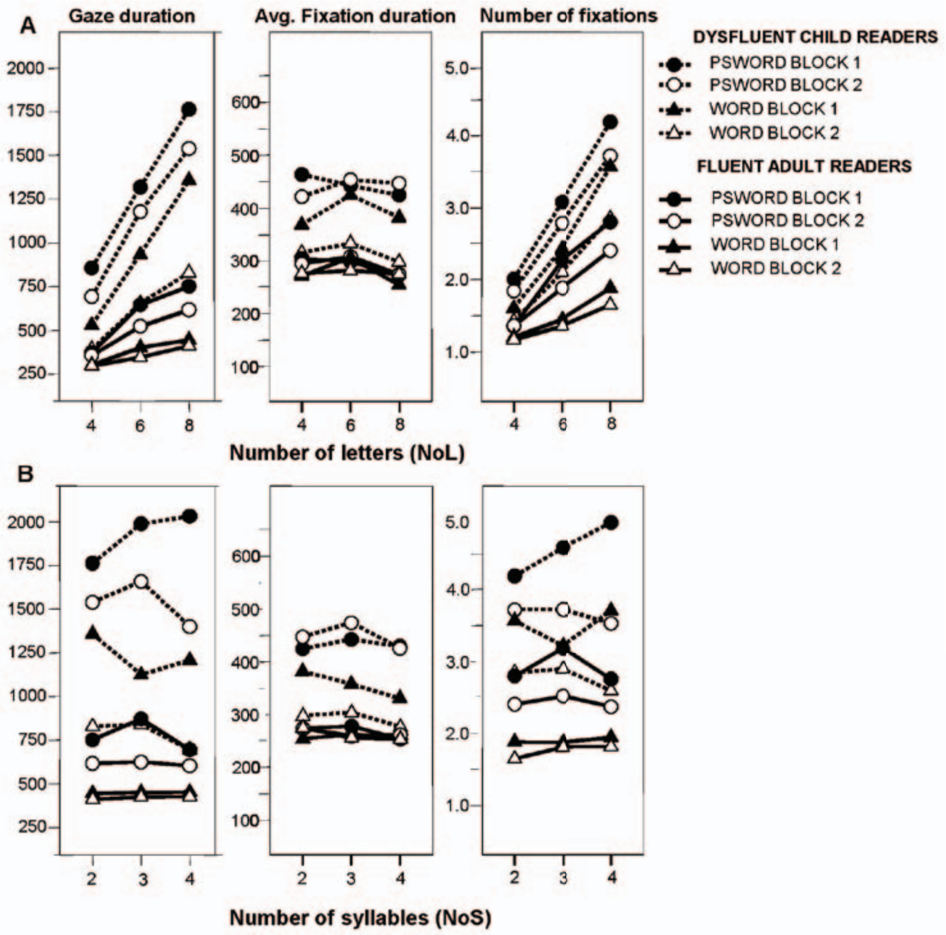
To attain equal variances between groups and to prevent proportionally equal effect sizes from producing artificial interactions in both between- and within-group analyses, logarithmically transformed values were analyzed (Salthouse & Hedden, 2002). For producing a significant interaction in logarithmically transformed values, the studied effects are likely to differ also in proportional values (Martens & de Jong, 2008). For example, if the magnitude of the word length effect in absolute values is 200 ms in pseudoword reading and 100 ms in word reading, the word length effect is 100 ms greater for pseudowords. However, if the average reading time for words is 500 ms and for pseudowords 1000 ms, the proportional magnitude of the length effect is the same for words (100 / 500 = 0.2) and pseudowords (200 / 1000 = 0.2).

The results are reported separately for the NoL and NoS manipulation. A separate section is also devoted to the lexicality effects. As lexicality was a common factor in both manipulations, all pseudowords and words were included in this analysis. The repetition effects, if not interacting with NoL and NoS, are reported in the lexicality section. For the sake of simplicity, only the highest-level interactions involving NoL, NoS, lexicality and repetition are reported in the Results section, and the more redundant main effects and interactions are listed in the Appendix. The means for the NoL and NoS manipulations are reported in Figure 1 and the means for the lexicality effects are reported in Figure 2.

NoL analyses

Gaze duration. A Lexicality x NoL x Group interaction, $F(2,30) = 4.86$, $p = 0.013$, $\eta_p^2 = 0.136$, resulted from only adults showing a steeper pseudoword than word length effect, as revealed by a significant Lexicality x NoL interaction for adults, $F(2,15) = 13.25$, $p = 0.000$, $\eta_p^2 = 0.453$. In children, the Lexicality x NoL interaction was not significant, $F < 1$. The Group x NoL interaction was significant only in word reading, $F(2,30) = 7.30$, $p = 0.006$, $\eta_p^2 = 0.186$, but not in the pseudoword condition, $F = 1.53$,

Figure 1. Results of the first-pass variables including gaze duration (left), average fixation duration (middle) and number of fixations (right). The upper panels (A) show the results of the number of letters manipulation and the lower panels (B) the results of the number of syllables manipulation. For both groups, data are plotted separately for pseudowords and words in block 1 and 2



indicating that the length effect was proportionally steeper for children only in word reading. Moreover, the Block x NoL interaction was also significant, F(2,30) = 4.00, p = 0.023, $\eta_p^2 = 0.114$, suggesting that the NoL effect was generally reduced by repetition. Although the three-way interaction of Group x Block x NoL was not significant, F < 1, Figure 1 raises doubts whether the length effect is really reduced by repetition within the dysfluent child group. An ANOVA computed separately for the two groups revealed that the reduction of the length effect by repetition was present in the adult group, F(2,15) = 6.67, p = 0.008, $\eta_p^2 = 0.471$, but not in children, F = 1.34.

Number of first-pass fixations. In the number of first-pass fixations, a three-way interaction of Lexicality x NoL x Group was significant, $F(2,30) = 8.94$, $p < 0.001$, $\eta_p^2 = 0.224$, as only adults showed a steeper pseudoword than word length effect: Children did not show a Lexicality x NoL interaction, $F < 1$, but adults did, $F(2,15) = 26.13$, $p < 0.001$, $\eta_p^2 = 0.777$. The Group x NoL interaction, indicating a steeper length effect for children, was significant in word reading, $F(2,30) = 10.07$, $p < 0.001$, $\eta_p^2 = 0.240$, but not in the pseudoword condition, $F < 1$. The Block x NoL interaction, $F(2,30) = 5.26$, $p = 0.008$, $\eta_p^2 = 0.145$, suggests that the NoL effect was generally reduced by repetition. Despite the absence of a three-way interaction of Group x Block x NoL, $F = 1.68$, the groups showed a somewhat different pattern of results: A reduction in the length effect due to repetition was present in the adult group, $F(2,15) = 7.22$, $p = 0.003$, $\eta_p^2 = 0.311$, but not in children, $F < 1$.

Average fixation duration. A Block x NoL interaction, $F(2,30) = 3.18$, $p = 0.048$, $\eta_p^2 = 0.093$, resulted from 6-letter items receiving slightly longer fixations than 4-letter items in block 1.

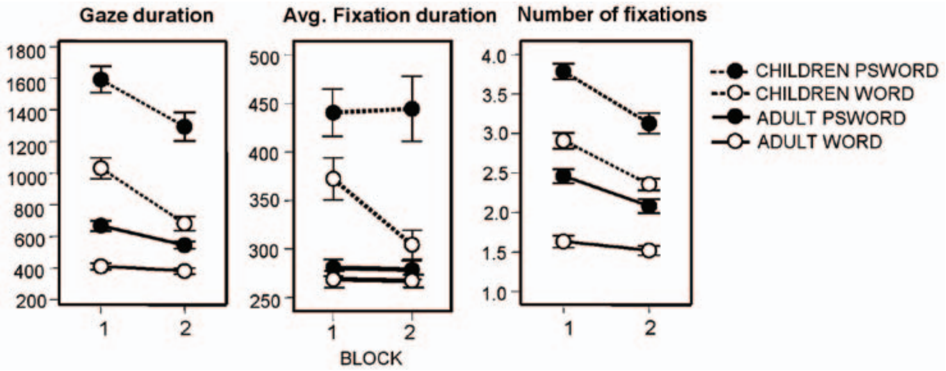
Summary. The most prominent finding was that adults consistently showed a stronger pseudoword than word NoL effect in gaze duration and fixation frequency, whereas in children the NoL effect was equally strong for pseudowords and words. The word, but not the pseudoword length effect was proportionally steeper for children than adults. Item repetition reduced the NoL effect in gaze duration and number of fixations for adults but not for children in these measures.

NoS analyses

Gaze duration. Gaze duration showed an almost significant four-way interaction of Group x Block x Lexicality x NoS, $F(2,30) = 3.12$, $p = 0.052$, $\eta_p^2 = 0.092$. The nature of this interaction is clear: Adults, but not children, $F = 2.5$, showed a three-way interaction of Block x Lexicality x NoS, $F(2,15) = 7.62$, $p = 0.002$, $\eta_p^2 = 0.323$. In adults there was a significant Lexicality x NoS interaction for block 1, $F(2,15) = 7.33$, $p = 0.002$, $\eta_p^2 = 0.314$, but not for block 2, $F < 1$. Trisyllabic pseudowords received longer gaze durations during block 1, as revealed by a contrast between bi- and trisyllabic pseudowords, $F(2,15) = 5.46$, $p = 0.033$, $\eta_p^2 = 0.254$. Children showed a significant interaction of Lexicality x NoS, $F(2,14) = 3.83$, $p = 0.047$, $\eta_p^2 = 0.354$, as the number of syllables had a slightly impeding impact on pseudoword reading and a slightly facilitating effect on word reading. However, when tested separately there was no effect of NoS either in the pseudoword or word condition, $Fs <= 1.5$. Children also showed a Block x NoS interaction, $F(2,14) = 4.69$, $p = 0.017$, $\eta_p^2 = 0.238$, as reading of four-syllabic items was facilitated the most by repetition, $F(2,14) = 9.44$, $p = 0.008$, $\eta_p^2 = 0.386$.

Number of first-pass fixations. The Block x NoS x Group interaction, $F(2,30) = 4.68$, $p = 0.013$, $\eta_p^2 = 0.131$, originates from the children demonstrating a greater reduction due to repetition in the number of fixations on four-syllable items, $F(2,14) = 4.57$, $p = 0.018$, $\eta_p^2 = 0.234$, whereas adults did not show the interaction, $F < 1$. The significant Block x Lexicality x NoS interaction, $F(2,30) = 3.99$,

Figure 2. Results for the lexicality effects. The dotted lines represent the dysfluent child readers and solid lines the fluent adult readers. Error bars of ±1 standard error are also shown



$p = 0.023$, $\eta_p^2 = 0.114$, indicates that slightly more fixations were made on trisyllabic pseudowords during block 1, $F(2,32) = 5.49$, $p = 0.007$, $\eta_p^2 = 0.143$, but not anymore during block 2, $F < 1$.

Average fixation duration. The main effect of NoS indicates that the shortest fixations were made on the four-syllable items, $F(2,30) = 4.79$, $p = 0.012$, $\eta_p^2 = 0.134$.

Summary. For adults the trisyllabic pseudowords were the most difficult items, as indicated by gaze duration, but this effect was reduced by repetition. Children did not show consistent effects of NoS across measures, except that repetition facilitated the reading of four-syllable items the most.

Lexicality and repetition effects

Gaze duration. The three-way interaction of Block x Lexicality x Group was significant, $F(1,31) = 15.35$, $p = 0.000$, $\eta_p^2 = 0.331$. In children word reading was more facilitated by repetition than pseudoword reading, $F(1,15) = 9.52$, $p = 0.008$, $\eta_p^2 = 0.338$, whereas in adults pseudoword reading was slightly more facilitated than word reading, $F(1,15) = 5.55$, $p = 0.032$, $\eta_p^2 = 0.258$. Both groups showed a robust lexicality effect during block 1 and 2 ($p < 0.001$). Repetition had a larger overall effect in children than in adults in word reading, as indicated by a Block x Group interaction, $F(1,31) = 30.60$, $p < 0.001$, $\eta_p^2 = 0.497$, but not in pseudoword reading, $F < 1$. Finally, the lexicality effect was greater for children than adults during block 2 only, $F(1,31) = 12.58$, $p = 0.001$, $\eta_p^2 = 0.289$.

Number of first-pass fixations. The Group x Lexicality interaction, $F(1,31) = 7.08$, $p = 0.012$, $\eta_p^2 = 0.186$, suggests a proportionally larger lexicality effect for adult readers, $F(1,31) = 6.89$, $p = 0.013$, $\eta_p^2 = 0.177$; yet also children showed a robust lexicality effect, $F(1,15) = 58.19$, $p < 0.001$, $\eta_p^2 = 0.784$. The Group x Block interaction,

$F(1,31) = 6.00$, $p = 0.020$, $\eta_p^2 = 0.162$, indicates that reduction due to repetition was larger for children, $F(1,15) = 7.08$, $p = 0.012$, $\eta_p^2 = 0.186$, than adults.

Average fixation duration. The three-way interaction of Block x Lexicality x Group interaction was significant, $F(1,31) = 5.05$, $p = 0.032$, $\eta_p^2 = 0.140$. Children showed a Block x Lexicality interaction, $F(1,15) = 8.43$, $p = 0.011$, $\eta_p^2 = 0.360$, whereas adults did not, $F < 1$. In word reading children greatly reduced their average fixation duration as a function of repetition, $F(1,15) = 17.24$, $p = 0.001$, $\eta_p^2 = 0.535$, whereas in pseudoword reading no significant reduction was present, $F < 1$. Adults did not show a reduction in average fixation duration due to repetition either in pseudoword or word reading, $Fs < 1$. The lexicality effect was greater for children both in block 1, $F(1,15) = 5.00$, $p = 0.032$, $\eta_p^2 = 0.135$, and in block 2, $F(1,15) = 12.58$, $p = 0.001$, $\eta_p^2 = 0.289$. Only children showed a lexicality effect in average fixation duration, $F(1,15) = 14.02$, $p = 0.002$, $\eta_p^2 = 0.467$ for block 1, and $F(1,15) = 29.59$, $p = 0.001$, $\eta_p^2 = 0.660$, for block 2.

Summary. Although children did not show a reduction in the word length effect (see previous analyses), they could reduce their overall number of fixations as a function of stimulus repetition and lexicality. Repetition also substantially shortened their average fixation durations on words, but not on pseudowords. Across all measures, the repetition effect tended to be slightly larger for children than for adults. Lexicality effects were robust for both groups in gaze duration and the number of fixations, whereas only children showed a lexicality effect in average fixation duration.

Discussion

To study to what extent words, letters and syllables are used as units in fluent and dysfluent decoding of transparent Finnish orthography and how relevant these units remain when the items become more familiar due to repetition, we measured eye movements during reading aloud of words and pseudowords, for which the number of letters and syllables were independently varied. In line with previous studies (summarized in the Introduction), we found a stronger pseudoword than word length effect in the number of fixations among fluent adult readers, whereas dysfluent children showed equally strong word and pseudoword length effects. A more novel finding was that stimulus repetition reduced the length effect especially in adults by decreasing the number of fixations, whereas children continued to be affected relatively similarly across repetitions by stimulus length. Interestingly, compared to dysfluent child readers, adults showed a proportionally weaker length effect in word, but not in pseudoword reading. The number-of-syllable manipulation produced only negligible effects. Oddly, adults fixated longest on the trisyllabic pseudowords, but this effect was reduced by repetition, whereas children reduced their number of fixations on four-syllabic items. Finally, compared to adults, children showed larger overall benefits of stimulus familiarity in terms of lexicality and repetition effects, particularly in word reading.

As argued in the Introduction, the number of fixations measure reflects the degree of lexical versus sublexical processing in word decoding, whereas the average fixation duration measure reflects the efficiency of word processing (Reichle et al., 2008; Hawelka et al., 2010). The number of fixations made on the target items seems to be determined by several factors. First, both groups showed the main effects of lexicality and repetition in the number of fixations. Both effects can be understood as reflections of stimulus familiarity and possibly sharing, at least partially, the same cognitive mechanism, perhaps at the visuo-orthographic level of processing (Risko, Stolz & Besner, 2010, Nazir et al., 2004), as will be discussed later. On the other hand, the magnitude of the word length effect in the number of fixations may be a more genuine measure of the quality of orthographic processing. However, the absolute magnitude of the word length effect is partially dependent on overall reading time, so proportional values should be analyzed (Di Filippo et al., 2006; Martens & de Jong, 2008), as was done in the present study. If the proportional length effect in the number of fixations is reduced by familiarity (i.e. words versus pseudowords), it is relatively safe to conclude that words are recognized more holistically than pseudowords. In the present study this was found only among fluent adult readers, but not among dysfluent children, suggesting a specific problem among young dysfluent readers in forming larger orthographic representations. This interpretation is further supported by the finding that dysfluent readers showed no reduction in the length effect due to repetition, whereas adult readers did.

According to the prevalent view, the word length effect stems from sublexical orthographic and phonological processing (Ziegler et al, 2003; Coltheart et al., 2001; Weekes, 1997). According to Share's (1995; 1999; 2004) self-teaching hypothesis, repeated reading produces word-level orthographic and phonological representations that bypass sublexical processing, thus relieving the word length effect. In Martens and de Jong's (2008) naming study repeated reading did not alter sublexical processing among beginning and dyslexic readers, with the exception that their fluent readers did not show a length effect at all. The authors discuss a variety of possibilities for repetition not reducing the length effect, including also the possibility that a reduction in the word length effect could be partly due to gradual development of an entire reading system and not primarily emerging from developing specific word representations. As regards fluent adult readers, Maloney et al. (2009) showed that even few repetitions are sufficient to reduce the pseudoword length effect. A similar reduction in the word and pseudoword length effect among fluent readers was observed in the present study. These findings may be taken to support the view of rapid formation of new orthographic representations among skilled readers (Ehri & Saltmarsh, 1995; Reitsma, 1983; Share, 1995; 1999; Maloney et al., 2009). Finally, it may be possible, as Martens and de Jong (2008) note, that repeated reading facilitates reading via priming. Priming should have quite a general influence on both word and pseudoword reading, contributing perhaps more to the main effect of repetition rather than to changes in processing style. Also, even in the priming account one has to assume that access to holistic representation is improved.

The number-of-syllables manipulation had only modest and not very straightforward effects in both groups, suggesting that the syllable plays at the most a subtle role in reading Finnish. These weak effects were affected by repetition – a result in line with Katz et al. (2001) who demonstrated a rapid fading of a large-unit regularity effect in lexical decision tasks, but not in naming. In the current study, adults fixated the trisyllabic pseudowords the longest, which suggests that some other factor than NoS may be responsible for the effect. However, adults overcame this difficulty by stimulus repetition suggesting again an ability to rapidly reduce sublexical processing and form new orthographic representations. Children showed a weak trend of initially fixating longer on the four-syllabic pseudowords than words, the effect being reduced by repetition, which may be taken as evidence for the ability for large-unit processing also among dysfluent readers, in addition to the dominant small-unit decoding.

As also our dysfluent children showed robust repetition and lexicality effects in the number of fixations, it seems that they have no deficit in taking advantage of stimulus familiarity. Assuming that their orthographic processing style remained letter-based, it may be that familiarity produces some sort of perceptual facilitation. Generally, perceptual learning is known to be specific to the trained stimuli and the retinal location, as reviewed by Gilbert, Sigman, and Crist (2001). Nazir et al. (2004) suggest that perceptual learning may affect early stages of visual processing during word recognition. In their lexical decision experiment, performance of briefly presented words was degraded as a function of horizontal displacement from fixation point, whereas pseudowords differing from the words only by the final letter did not show this sensitivity to horizontal displacement. Risko et al. (2010) showed that repeated words require less spatial attention and suggest that repetition may improve orthographic feature and letter-level processing. Dykes and Pascal (1981) even found that the repetition of the letter C improved the recognition of the visually similar letter G but not that of the dissimilar letter F. In our study, repetition may have activated visual representations of words and pseudowords, and these visual representations may have provided a beneficial context for feature and letter extraction.

Even when expected, it is surprising that the dysfluent children could not use their lexical knowledge to make the laborious sublexical reading procedure easier. As a very limited set of words was used, one could have adopted a strategy of guessing the word based on its initial letters.

However, the length effect in the number of fixations was not affected by the familiarity of lexical items. On the other hand, average fixation duration on words, but not on pseudowords, was clearly shortened (effect size was $\eta_p^2 = 0.54$) among children; this finding was also reflected in the gaze duration measure. Similarly to the present study, Judica et al. (2002) demonstrated shortened fixation durations as a response to a speeded word recognition training in normal and dyslexic Italian children. This was interpreted to suggest that speeded training increased the amount of visual information gathered by each fixation. An alternative account for these results would be a more strategic explanation – the dysfluent children may resort to a sublexical reading strategy even when they have quite a good idea what the word is. One apparent motive for this strategy would be to avoid mistakes.

In conclusion, the fixation frequency and duration data may be interpreted as suggesting that dysfluent child readers use a sublexical route even when reading aloud highly familiar words; an increase in familiarity facilitates perceptual and visuo-orthographic processing, but does not introduce a change in the processing strategy. This may be taken to suggest that dysfluent children seem to have a deficit in rapidly forming larger orthographic representations as a result of item repetition. Further studies of repeated reading with a more extensive repetition procedure are needed to find out to what extent the word length effect could be reduced in dysfluent reading.

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Appendix

Significant interactions and main effects redundant to higher-level interactions, not reported in the Results section.

NoL analyses

Gaze duration. Group, F(1,31) = 78.81, $p < 0.001$, $\eta_p^2 = 0.718$, Block, F(1,31) = 57.79, $p < 0.001$, $\eta_p^2 = 0.651$, Lexicality F(1,31) = 169.47, $p < 0.001$, $\eta_p^2 = 0.845$, NoL, F(2,30) = 145.00, $p < 0.001$, $\eta_p^2 = 0.824$, Block x Lexicality, F(1,31) = 5.00, p = 0.033, $\eta_p^2 = 0.139$.

Number of first-pass fixations. Group, F(1,31) = 78.81, $p < 0.001$, $\eta_p^2 = 0.718$, Lexicality F(1,31) = 186.32, $p < 0.001$, $\eta_p^2 = 0.857$, NoL, F(2,30) = 215.13, $p < 0.001$, $\eta_p^2 = 0.874$, Lexicality x Group, F(1,31) = 7.65, p = 0.009, $\eta_p^2 = 0.198$, Lexicality x NoL, F(2,30) = 8.19, $p < 0.001$, $\eta_p^2 = 0.209$.

Average fixation duration. Group, F(1,31) = 18.39, $p < 0.001$, $\eta_p^2 = 0.372$, Block, F(1,31) = 9.38, p = 0.005, $\eta_p^2 = 0.232$, Lexicality F(1,31) = 28.80, $p < 0.001$, $\eta_p^2 = 0.482$, NoL, F(2,30) = 6.14, p = 0.004, $\eta_p^2 = 0.165$, Block x Group, F(1,31) = 9.17, p = 0.005, $\eta_p^2 = 0.228$, Lexicality x Group, F(1,31) = 9.69, p = 0.004, $\eta_p^2 = 0.238$, Block x Lexicality, F(1,31) = 5.86, p = 0.022, $\eta_p^2 = 0.159$.

NoS analyses

Gaze duration. Group, F(1,31) = 93.91, p = 0.000, $\eta_p^2 = 0.752$, Block, F(1,31) = 75.64, p = 0.000, $\eta_p^2 = 0.709$, Lexicality F(1,31) = 159.43, p = 0.000, $\eta_p^2 = 0.837$, NoS, F(2,30) = 3.22, p = 0.047, $\eta_p^2 = 0.094$ Block x Lexicality x Group, F(1,31) = 10.31, p = 0.003, $\eta_p^2 = 0.250$, Block x Syllables x Group, F(2,30) = 4.02, p = 0.023, $\eta_p^2 = 0.115$, Lexicality x Syllables x Group, F(2,30) = 4.39, p = 0.016, $\eta_p^2 = 0.124$, Block x Lexicality x Syllables, F(2,30) = 4313, p = 0.019, $\eta_p^2 = 0.122$.

Number of first-pass fixations. Group, F(1,31) = 62.64, p = 0.000, $\eta_p^2 = 0.669$, Block, F(1,31) = 125.00, p = 0.000, $\eta_p^2 = 0.801$, Lexicality F(1,31) = 120.39, p = 0.000, $\eta_p^2 = 0.669$, Block x Group, F(1,31) = 6.37, p = 0.017, $\eta_p^2 = 0.171$, $\eta_p^2 = 0.795$, Lexicality x Group, F(1,31) = 7.63, p = 0.010, $\eta_p^2 = 0.198$.

Average fixation duration. Group, F(1,31) = 25.40, p = 0.000, $\eta_p^2 = 0.450$, Block, F(1,31) = 5.10, p = 0.031, $\eta_p^2 = 0.14$, Lexicality F(1,31) = 28.08, p = 0.000, $\eta_p^2 = 0.475$, Lexicality x Group, F(1,31) = 17.28, p = 0.000, $\eta_p^2 = 0.358$, Block x Group, F(1,31) = 5.08, p = 0.031, $\eta_p^2 = 0.141$.

Lexicality and Repetition analyses

Gaze duration. Group, F(1,31) = 88.57, $p < 0.001$, $\eta_p^2 = 0.741$, Block, F(1,31) = 172.21, $p < 0.001$, $\eta_p^2 = 0.847$, Lexicality F(1,31) = 93.03, $p < 0.001$, $\eta_p^2 = 0.750$, Lexicality x Group, F(1,31) = 14.82, p < = 0.001, $\eta_p^2 = 0.323$.

Number of first-pass fixations. Group, $F(1,31) = 78.81$, $p < 0.001$, $\eta_p^2 = 0.718$, Lexicality $F(1,31) = 129.42$, $p < 0.001$, $\eta_p^2 = 0.807$, Block, $F(1,31) = 162.66$, $p < 0.001$, $\eta_p^2 = 0.840$.

Average fixation duration. Group, $F(1,31) = 23.26$, $p < 0.001$, $\eta_p^2 = 0.429$, Block, $F(1,31) = 32.98$, $p < 0.001$, $\eta_p^2 = 0.515$, Lexicality $F(1,31) = 10.02$, $p = 0.003$, $\eta_p^2 = 0.244$, Block x Group, $F(1,31) = 16.21$, $p < 0.001$, $\eta_p^2 = 0.343$, Lexicality x Group, $F(1,31) = 6.89$, $p = 0.013$, $\eta_p^2 = 0.182$, Block x Lexicality, $F(1,31) = 5.59$, $p = 0.024$, $\eta_p^2 = 0.153$.

II

The role of letters and syllables in typical and dysfluent reading in a transparent orthography

by

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Abstract

The role of letters and syllables in typical and dysfluent 2nd grade reading in Finnish, a transparent orthography, was assessed by lexical decision and naming tasks. Typical readers did not show reliable word length effects in lexical decision, suggesting establishment of parallel letter processing. However, there were small effects of word syllable structure in both tasks suggesting the presence of some sublexical processing also. Dysfluent readers showed large word length effects in both tasks indicating decoding at the letter-phoneme level. When lexical access was required in a lexical decision task, dyslexics additionally chunked the letters into syllables. Response duration measure revealed that dysfluent readers even sounded out the words in phoneme-by-phoneme fashion, depending on the task difficulty. This letter-by-letter decoding is enabled by the transparent orthography and promoted by Finnish reading education.

Keywords: syllables; word length; lexicality; developmental dyslexia; phonological decoding

1 Introduction

The core of reading in alphabetical writing systems involves the conversion of written to spoken language (for reviews, see Frost, 1998; Rayner, Foorman, Pesetsky, & Seidenberg, 2001), in which dyslexics are deficient (for reviews see Rayner et al., 2001; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Here, we address which linguistic units impact reading in Finnish, a fully transparent orthography, by manipulating independently the lexical status, number of letters and number of syllables of words. Moreover, we explore how these stimulus effects vary as a function of reading skill and task by examining young typical and dysfluent readers in the second grade in visual word naming and lexical decision tasks.

In English, there are approximately 1,500 grapheme-phoneme connections to be mastered (Goswami, 1995) in reading. Evidence from acquired dyslexics suggesting selective impairment in reading either pseudowords or words with irregular spelling-to-sound correspondences (for a review, see Coltheart, 2004) led to the development of visual word recognition models that include options or routes for holistic word recognition and phonological decoding or simply decoding (e.g., Dual-Route Cascaded (DRC) Model; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). The former type of processing is characterized as uninfluenced by sublexical properties of words, whereas in the phonological route, sublexical influences arise from a systematic conversion of graphemes to phonological representations. In transparent orthographies each letter may correspond to one phoneme and vice versa, as is the case in Finnish, the language of the present study (Aro, 2006; Karlson, 1999). According to the orthographic depth hypothesis (for a review see Katz & Frost, 1992), the transparency of the orthography-to-phonology mapping facilitates decoding, and therefore the entire process of reading acquisition (Aro & Wimmer, 2003; Seymour, Aro, & Erskine, 2003). A commonly used marker for decoding in transparent orthographies is word length effect, i.e. the impeding effect of the number of letters (De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Weekes, 1997), which indeed has been found to be larger in transparent than opaque orthographies (Ziegler, Perry, Jacobs, *&* Braun, 2001; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003) and more commonly observed in visual word naming than in the lexical decision task (Ferrand & New, 2003; Frederiksen & Kroll, 1976). However, word length effects may be absent in fluent reading in transparent orthographies (see Hawelka, Gagl, & Wimmer, 2010 for eye movement evidence in silent reading and Martens & de Jong, 2008, and Spinelli, De Luca, Di Filippo, Mancini, Martelli, *&* Zoccolotti, 2005, for word naming latencies), suggesting that fluent readers may be capable of holistic word recognition as well.

It is possible that larger sublexical units than letters are used for decoding (Ans, Carbonnel, & Valdois, 1998; Ferrand, 2003). Syllables are natural building blocks of all spoken words, being suitable units for orthography-to-phonology mapping (see Álvarez, Carreiras, & Perea, 2004; Spoehr & Smith, 1973) and impeding effects of the number of syllables on word recognition accuracy (Spoehr & Smith, 1973) and on pseudoword reading speed in particular have been found across orthographies (Ferrand, 2000; Ferrand & New, 2003; Jared & Seidenberg, 1990; New, Ferrand, Pallier, & Brysbaert, 2006; Stenneken, Conrad, Jacobs, 2007). Gagl, Hawelka, & Wimmer (2010) followed the development of word recognition skills from Grades 2 to 4. They found that the number of syllables had an impeding effect on reading speed only at Grade 2. Thus, it is expected that in typical readers, syllable effects may be present in both word and pseudoword reading, but are larger in the latter type of items.

The present study assesses the extent to which decoding, as indexed by word and syllable length effects, is involved in children's word and pseudoword reading in naming and lexical decision tasks. In naming tasks, a detailed phonological code is required (Frost, 1998) in order to correctly produce a spoken output, potentially increasing the phonological effects. In lexical decision tasks, only lexical access is required, which may not require detailed phonological decoding (Frost, 1998). Empirical comparisons of naming and lexical decision latencies confirm these predispositions (Baayen, Feldman, & Schreuder, 2006; Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2006).

In addition to the stimulus and task manipulations, the present study also examines how effects are modulated by reading skill by examining cohorts of fluent and dysfluent second-grade readers. The behavioral manifestation of dyslexic reading is known to reflect properties of writing systems – in transparent writing systems dyslexic reading is characterized by slow reading (Wimmer, 1993, 1996a, 1996b), whereas in opaque orthographies dyslexics also make a substantial amount of errors (for review, see Rack, Snowling, *&* Olson, 1992). Dyslexic reading in transparent orthographies is characterized by striking word and pseudoword length effects present in eye fixations (De Luca et al., 1999; De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; Hutzler & Wimmer, 2004), naming response times (De Luca, Burani, Paizi, Spinelli, & Zoccolotti, 2010; De Luca, Barca, Burani, & Zoccolotti, 2008; Martens & de Jong, 2008; Ziegler et al., 2003; Zoccolotti, De Luca, Judica, & Spinelli., 2008) and in lexical decision response times (Di Filippo, De Luca, Judica, Spinelli, & Zoccolotti, 2006; Juphard, Carbonnel, & Valdois, 2004; Martens & de Jong, 2006). Slowness has been found even in naming single letters (De Luca et al., 2010). To our knowledge, the present study is the first that looks into the unique effect of the number of syllables in poor reading. As poor readers are expected to read mainly by decoding, we predict a syllable length effect both in word and pseudoword reading.

For beginning readers phonological decoding is a tool for independently learning new words and for increasing word-specific knowledge as suggested by Share (1995). Undoubtedly, poor and beginning decoding is cognitively a more complicated and effortful process than fluent decoding (Share, 1995). For dyslexics effortful decoding may be the predominant way of reading if the word recognition processes are not automatized (Pugh et al., 2008). In the naming task, fluent readers seem to start their naming response only after assembling the phonological code of the item (Rastle, Harrington, Coltheart, & Palethorpe, 2000; but see Kawamoto, Kello, Jones, & Bame, 1998). However, the response duration has been also found to be sensitive for stimulus properties independent of the response onset in some conditions – the authors inferred that this processing was related to the meaning of the words in English (Balota, Boland, & Shields, 1989). Particularly in transparent orthographies – in which the pronunciation of letters is not affected by orthographic context – the assembly of a complete phonological code before a response onset may not be necessary (Hutzler, Conrad, *&* Jacobs, 2005). This strategy may be easier for poor and early readers, allowing them to utilize their vocalization in the assembly process. If dissociations in response onset times and response durations in the naming task are found, this may suggest that children exploit such an online decoding strategy. The online decoding strategy may be a general reading strategy, therefore the interest is to study whether this strategy usage is affected by item properties.

In Finnish each letter of the alphabet corresponds to a unique phoneme and vice versa, with the exception of the grapheme 'ng', which corresponds to long quantity of the phoneme /ŋ/ (Aro, 2006; Karlsson, 1999). The syllabification in Finnish is determined by simple rules, denoting a syllable boundary before every sequence of a single consonant followed by a vowel, and a syllable boundary between vowels not constituting a diphthong (Karlsson, 1999). In addition, the syllable structure is fairly simple with only ten possible CV-structures and the number of different syllables is rather limited (~ 3,000) (Karlsson, 1999). The initial syllable of a word is always stressed (Karlsson, 1999), followed by a secondary stress on every other syllable in a word except the final syllable. As the present study utilizes only two- and three-syllable items, only the initial syllable is stressed. Being limited in number, frequently occurring, easily parsed, and prosodically distinct, syllables seem good candidates for decoding units in Finnish. Finnish has a complex agglutinative morphology, a productive derivational system and compounding (Karlsson, 1999). Agglutination leads to long words, which are not recognizable by a single fixation due to restrictions of visual acuity (Bertram & Hyönä, 2003). Studies have found that morphological decomposition is typically required to read Finnish words (Hyönä, Bertam, & Pollatsek, 2004), although constituent and compound frequency effects suggest the existence of word representations (Hyönä et al., 2004). These factors alleviate some of the sublexical processing that typically takes place even in fluent reading of Finnish.

Reading instruction in Finnish is systematically based on phonics. Nearly every child learns to decode in the first grade (Lerkkanen, 2007), and the literacy curriculum in the second grade focuses on fluency and reading comprehension. Moreover, reading and spelling skills are taught simultaneously and children usually acquire both skills confidently. Syllabification has been found to be instrumental for learning to read and especially spell, and is standardly used in early reading education and even explicitly marked in early reading materials. While learning the letter sounds in first grade, children are simultaneously practicing decoding with the letters already mastered. Typically this is carried out with syllables, and hyphenated words where they read syllable-by-syllable by slowly “sliding” from one phoneme sound to another in the hyphenated syllables (Lerkkanen, 2007).

Here, typical and dysfluent reading in the transparent Finnish orthography is studied among 8-year-old children in the second grade. The first research question examines the extent to which typical readers demonstrate phonological decoding. We take as our index of holistic word recognition a lack of number of letter or syllable length effect, particularly in lexical decision tasks (Di Filippo et al., 2006; Martens & De Jong, 2006), whereas in naming tasks such phonological effects may be present (De Luca et al., 2002, 2009; Martens & de Jong, 2008 ; Zoccolotti et al., 2005, 2008). The dysfluent readers are expected to yield large responses to lexicality and the number of letter manipulation in both the lexical decision (Di Filippo et al., 2006; Martens & de Jong, 2006) and naming tasks(De Luca et al., 2002, 2008, 2009; Martens & De Jong, 2008; Zoccolotti et al., 2005, 2008). Second, the possible role of the syllable in decoding in Finnish is studied. The influence of the number of syllables (Ferrand, 2000; New et al., 2006; Stenneken et al., 2007) is expected to be larger in pseudoword than word reading in controls. Due to their decoding-based reading style, dysfluent readers are expected to show syllable effects both in word and pseudoword reading, irrespective of the task. Finally, the separation of response onset and response duration measures in the naming task should reveal if children rely on the online decoding strategy.

2 Method

2.1 Participants

The participants were 40 children (21 girls, 19 boys) taking part in a three-year longitudinal study from Grade 1 to Grade 3. Only the results from the second grade are reported here.

2.2 Reading and cognitive skill assessment

The behavioral testing for the 40 participants consisted of assessment of general intellectual abilities (WISC-III, seven subscales), followed by testing of reading skills. The inclusion criterion of a full IQ of at least 80 led to the exclusion of one participant. Performance in three reading tasks was taken into account when dividing children into two groups, dysfluent (DYS) and typical chronological age matched (CA) readers: Time-limited reading of (1) word (Lukilasse Graded Fluency Test; Häyrinen, Serenius-Sirve, & Korkman, 1999) and (2) pseudoword lists were both scored based on the total number of correctly read items (aloud) within the space of 45 seconds and (3) text reading fluency, assessed through oral reading tasks (a meaningful story “Exciting adventures,” 124 words long) with measures of both speed (words per minute) and accuracy (number of correct words per minute) (Lyytinen et al., 2005).

The scores of all three reading tasks were z-scored using the mean and standard deviation from a normative sample of 363 second graders derived from the longitudinal First Step Study (Lerkkanen et al., 2006). A child was considered a dysfluent reader if he or she had an average score across the three tests of more than 1.25 standard deviations below the mean. Children with z-scored averages above -1.0 were included in the control group. Three subjects scored between these cutoff scores and their data was excluded from the analyses. With these criteria, 12 of the 39 children were considered dysfluent readers and 24 children constituted the typical readers as a control group. For various reasons including fatigue and technical problems, data was lost for one DYS and two CA in the naming task, and for four DYS and one CA in the lexical decision task. Therefore, a full dataset was acquired from 8 DYS and 20 CA participants. Table 1 presents means and standard deviations of demographic variables. Small group differences were observed with the size of 11 in performance IQ, $t(32) = 2.36$, p = .028, and with the size of 9 in full IQ, $t(32) = 2.28$, p = .032.

Table 1 Demographic statistics of the children belonging to dysfluent (DYS) and control (CA) groups.

	DYS	CA	*t*(33)	*p*
N	12	24		
Age (months)	105 (3)	106 (4)	.061	.952
Verbal-IQ	99 (9)	102 (13)	.-686	.443
Performance-IQ	86 (13)	97 (14)	2.36	.028
Full-IQ	91 (8)	99 (10)	2.28	.032

2.3 Stimuli

In both the naming and lexical decision tasks, there were three categories of words and pseudowords, each consisting of 25 items: bisyllabic four-letter, bisyllabic six -etter and trisyllabic six-letter items. Words were common Finnish words familiar to children and controlled for frequency (Kotimaisten kielten tutkimuskeskus, 2007; see Table 2 for frequency counts and Appendix for lists of experimental items). Pseudowords conforming to Finnish phonotactics were constructed from the words by replacing two letters. Different words and pseudowords were used in lexical decision and naming tasks. The items contained no foreign letters (b,c,d,f,q,z,w,x,å). As Finnish syllabification is simply dictated by the consonant-vowel structure of two consecutive letters (or phonemes), the manipulation of the number of syllables when the number of letters is controlled for always produces different consonant-vowel structures in bi- and trisyllabic items (a syllabified example: *ka.ra.ta* (escape), *kart.ta* (map), *kar.tat* (maps)).

Table 2 Mean surface word frequencies of the items used in the experimental tasks. Values are expressed as occurrences in a million word with standard deviations in parenthesis. L = letters, S=syllables.

	Word type		
	4L2S	6L2S	6L3S
Naming	16 (14)	15 (25)	14 (17)
Lexical decision	16 (24)	9 (15)	12 (19)

Note: Due to hundreds of inflected word forms of the same base word frequency values are lower in Finnish than what is typically seen in English. Nonetheless the words were common Finnish words familiar to children as shown by high accuracy data reported in Results -section.

2.4 Procedure

The naming and lexical decision tasks were presented using Cognitive Workshop v.1.11 software with a laptop computer. All participants received the naming task first, followed by the lexical decision task. During each trial, subjects saw a fixation cross in the center of the screen for 1000 msec, followed by an item presented in white lower-case Arial 72-point font on a black screen. The item remained on the screen until the response was completed. There was a 2000 msec blank-screen interval between the trials.

Naming. Items were blocked by a stimulus type such that all words were presented prior to pseudowords and stimuli within each block were presented in random order for each subject. Participants were asked to read the items aloud as fast and accurately as they could. The experimenter (a trained research assistant) had to decide after each trial whether the response was correct or not, providing no feedback for the participant. The subjects' utterances were recorded into audio files where voice onset and offset trigger marks were added by means of a voice key.

Lexical decision. Words and pseudowords were mixed and presented in random order in two blocks with a brief pause between blocks. The trials had the same parameters as in the naming task. WORD and PSEUDOWORD responses were indicated by pressing colored buttons on a laptop computer.

2.5 Data processing

A research assistant checked and corrected the automatic voice onset and offset triggers from the sound files as necessary. This was obligatory because the voice key cannot handle various aspects of vocal responses for example non-response sounds such as loud breathing and silent pauses at syllable boundaries consisting of stop consonants. Only valid trials and correct responses were included in response time and duration analyses. In the naming task there were 1.9% invalid trials (89), due to failure of voice onset or offset trigger. Reaction times shorter than 350 msec were excluded (11 or 0.2% of all responses). Reaction times longer than 3 SD from each subject-pseudo/word average were excluded from the analyses (76 or 1.6% of all responses). In the lexical decision task, reaction times shorter than 600 msec (17 or 0.3% of all responses), invalid trials (20 or 0.4% of all responses), and reaction times longer than 3 SD from each subject-word/pseudoword average (83 trials or 1.7% of all responses) were excluded from the analyses.

3 Results

3.1 Data analysis

The lexicality, number of letter (NoL), and number of syllable (NoS) manipulations provide information on the recognition units. The comparison between the total response time in naming (the sum of response onset time and response duration) and the lexical decision response times reveal whether the relevance of the units is dependent on task requirements, and the comparison of response onset times and response durations in naming should reveal whether the children continue the decoding during their responses.

First, to see which of the studied effects contribute to reading fluency, we analyzed – with continuous variables and including all 39 subjects in the analysis – the partial correlations of the studied effects with reading fluency when the performance IQ was controlled for. In addition, the influence of word frequency was studied by dividing each class of words into two equal halves according to their word frequency values. Next, to examine the difference between dysfluent (n = 8) and typical readers (n = 20) in the studied effects, we administered an analysis of variance for repeated measures using group (DYS, CA) as a between-subject factor, whereas task (naming, lexical decision), measure (naming onset response time, naming response duration), lexicality (words, pseudowords) and item type (4L2S, 6L2S, 6L3S) were handled as within-subject factors. A planned repeated contrast of item type factor would reveal whether the effect resulted from manipulation of the number of letters (4L2S vs. 6L2S) or number of syllables (6L2S vs. 6L3S). The performance IQ value was added as a covariate to rule out the possible effect of the small difference between groups in overall cognitive level regarding reading speed.

The mean accuracy rates for the studied effects are reported in Table 3. Generally the accuracy was high; in the naming task the mean accuracy was 87% for DYS group and 94% for CA group, and in the lexical decision task the mean accuracy was 92% for DYS group and 95% for CA group. Because of the ceiling – particularly in CA group – and to avoid spurious results, accuracy rate analyses were omitted.

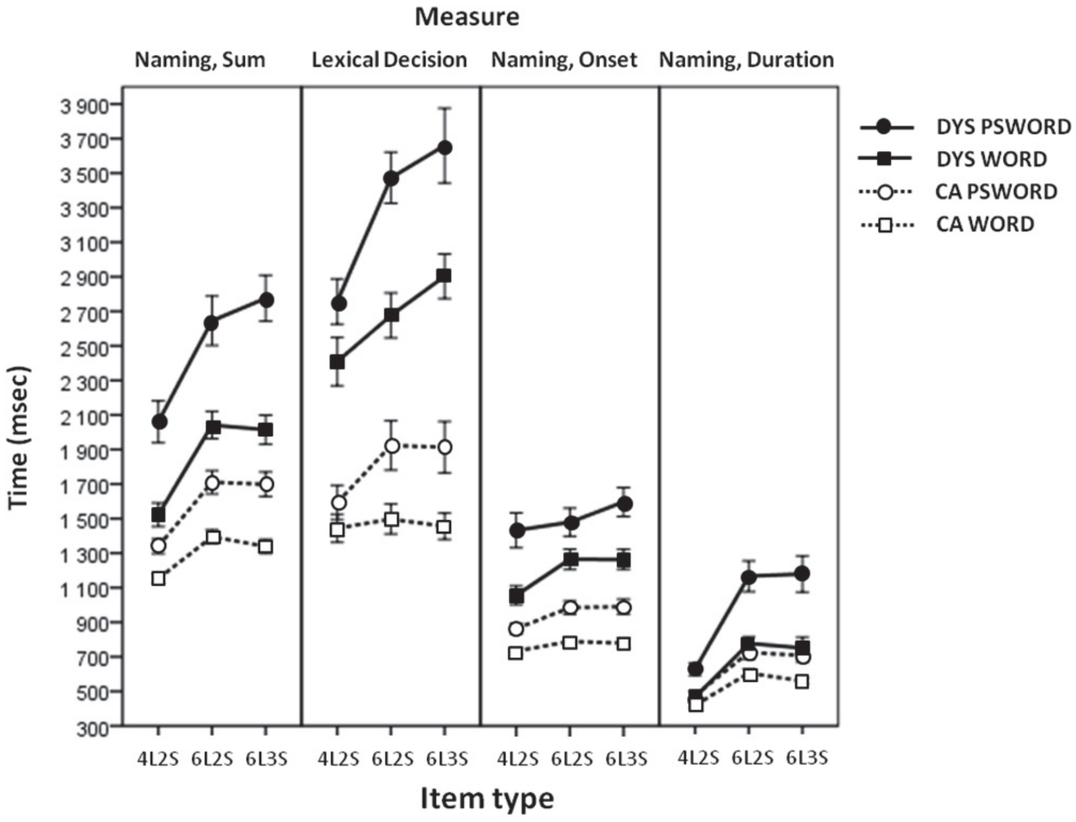
Table 3 Accuracy Percentages with Standard Deviations in Parenthesis.

		Words			Pseudowords		
	Group	4L2S	6L2S	6L3S	4L2S	6L2S	6L3S
Naming	DYS	94.1 (4.5)	86.9 (5.0)	91.6 (9.0)	85.0 (14.1)	82.1 (6.7)	81.4 (8.9)
	CA	97.3 (2.9)	96.0 (3.0)	96.7 (4.9)	94.8 (5.3)	89.5 (7.6)	91.6 (5.4)
Lexical Decision	DYS	84.8 (10.1)	87.6 (12.0)	95.9 (5.6)	92.0 (6.9)	93.3 (6.5)	96.9 (4.1)
	CA	88.5 (6.5)	95.4 (4.3)	96.5 (4.0)	96.1 (4.2)	95.7 (5.7)	95.6 (5.5)

3.2 Partial correlations of the studied effects to reading fluency

It appeared that lexicality effects both naming, $r(31) = -.721$, $p < .001$, and lexical decisions, $r(31) = -.621$, $p < .001$, and pseudoword NoL effects in lexical decision, $r(31) = -.612$, $p = .001$, word NoL effect in naming, $r(32) = -.685$, $p < .001$, and differential naming onset and duration measure, $r(32) = -.555$, $p = .001$, had highly significant correlations with reading fluency. Moreover, pseudoword NoL effect naming, $r(31) = -.527$, $p = .002$, task, $r(28) = -.480$, $p = .007$,and word frequency effect in naming, $r(32) = -.467$, $p = .005$, had intermediate correlations to reading fluency. Instead, any of the NoS effects, or word NoL and frequency effects in lexical decision did not correlate significantly with reading fluency.

Figure 1 Group averages of reaction times in the experimental tasks.



Error Bars: +/- 1. SE

3.3 Task comparison

In the comparison of total naming response tim and lexical decision response times, the following main effects were significant or near-significant: task, *F*(1.25) = 4.05, *p* = .055, = .139, lexicality, *F*(1.25) = 6.90, *p* = .015, = .216, item type, *F*(2.24) = 7.45, *p* = .003, = .383, and group, *F*(1.25) = 57.5, *p* < .001, = .697. The main effect of the IQ covariate was not significant, *F*(1.25) = 1.54, *p* = .226, = .058, and it did not interact with any of the independent variables studied.

A highly significant Group x Item type interaction, *F*(2.24) = 21.9, *p* < .001, = .646, indicated that the NoL effect was generally larger for DYS group (503 msec) than CA group (244 msec), irrespective of the task or lexical status of the item. Group x Lexicality interaction, *F*(1.25) = 9.06, *p* = .006, = .266, showed that the influence of lexical status was greater on reading for DYS group (630 msec) than for CA group (304 msec). Group x Task interaction, *F*(1.25) = 13.07, *p* = .001, = .343, indicated that the influence of task was larger for DYS group (790 msec) than CA group (180 msec).

There was a significant three-way interaction of Group x Task x Item type, *F*(2.24) = 3.83, *p* = .036, = .242, stemming from the NoS manipulation, *F*(1.25) = 6.52, *p* = .017, = .207. The DYS group demonstrated an impeding effect of NoS with the size of 242 msec in the lexical decision task, *F*(1.7) = 8.98, *p* = .020, = .562, whereas the CA group did not show any syllable effect, *F* = .739.

In the naming task, Lexicality x Item type interaction was significant, *F*(1.30) = 24.68, *p* = .000, = .630, stemming from both NoL, *F*(1.30) = 6.55, *p* = .016, = .179, and NoS manipulations, *F*(1.30) = 8.38, *p* = .007, = .219. The number-of-letter effect was larger for pseudowords (478 msec) than for words (380 msec), and trisyllabic relative to bisyllabic words were responded to 42 msec faster, *F*(1.30) = 5.02, *p* = .032, = .139. Although the three-level interaction of Group x Lexicality x Item type was not significant, *F* = 1.42, within groups CA group showed Lexicality x NoL interaction as a sign of specialized letter processing for words, *F*(1.20) = 11.12, *p* = .003, = .358, whereas DYS group did not, *F* = .768.

In the lexical decision task, Lexicality x Item type interaction was significant, *F*(2.28) = 15.55, *p* < .000, = .526, stemming only from NoL, *F*(1.29) = 30.13, *p* < .001, = .510, not NoS manipulation, *F* = .004. CA group showed no difference (2 msec) in response times between 4L2S and 6L3S words, *F* < .003, suggesting a capacity for parallel letter processing. However, response times were 48 msec slower for 6L2S than 4L2S words, *F*(1.22) = 4.83, *p* = .039, = .187, which may indicate a presence of some structural coding of words.

3.4 Comparison of different measures in naming task

The response onset time and response duration in the naming task were significantly influenced by the following main effects: lexicality, *F*(1.29) = 6.20, *p* = .019, = .176, item type, *F*(2.28) = 4.53, *p* = .020, = .244, group, *F*(1.29) = 52.7, *p* < .001, = .645. Again, performance IQ did not produce a main or interaction effect.

The two-level Group x Item type interaction, *F*(2.28) = 19.86, *p* < .001, = .587, stemming from NoL manipulation, *F*(1.29) = 17.98, *p* < .001, = .383, reflected an overall larger NoL (546 msec) effect in DYS group than in CA group (130 msec). The two-level Group x Measure, *F*(1.29) = 17.1, *p* < .001, = .371, indicated that the difference between DYS and CA was larger in response onset time (492 msec) than in response duration (250 msec).

Most importantly, the four-level interaction of Group x Measure x Lexicality x Item type was significant, *F*(2.28) = 6.34, *p* = .005, = .313, as well the three-level interaction of Group x Measure x Item type, *F*(2.28) = 4.66, *p* = .018, = .250. Both interactions stemmed from NoL manipulation, *F*(1.29) = 8.48, *p* = .007, = .226, and *F*(1.29) = 12.28, *p* = .002, = .297, respectively. Next, this four-level interaction is explored in detail in separate partial ANOVAs for response onset and duration measures.

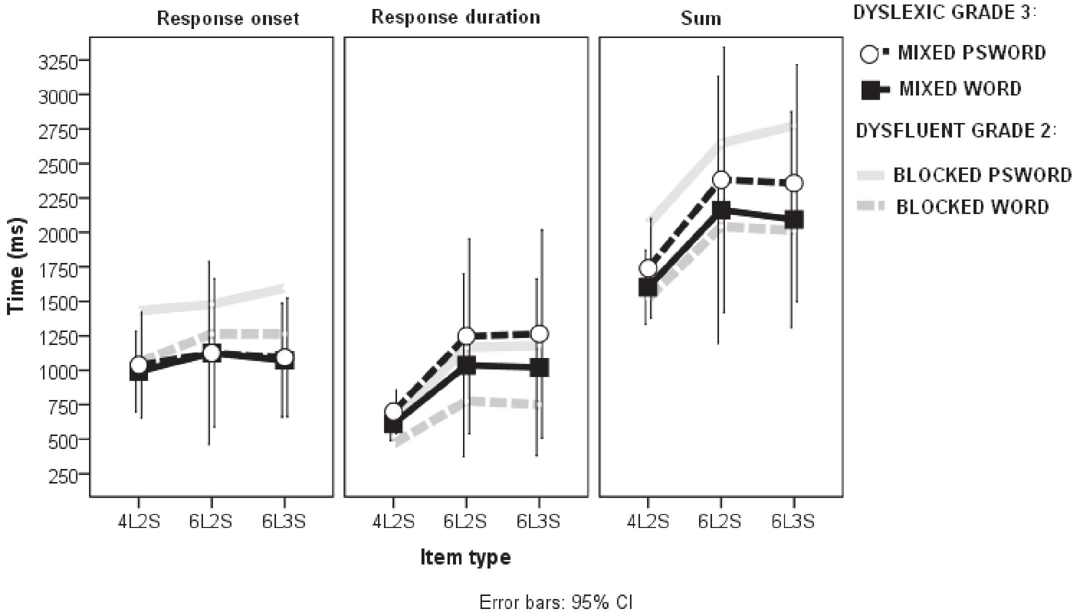
Response onset times. The three-way interaction of Group x Lexicality x Item Type was significant, *F*(2.29) = 7.96, p = .002, = .354, stemming from both NoL, *F*(1.30) = 14.42, p < .001, = 325, and NoS manipulations, *F*(1.30) = 5.61, p < .001, = .158. Figure 1A reveals the nature of these interactions: the DYS group presents a steeper word, *F*(1,30) = 13.09, p < .001, = .304, but not pseudoword NoL effect, *F* = 2.64, than CA group. Note that this counter-intuitively small pseudoword NoL effect in DYS will be compensated for by a striking pseudoword NoL effect in response durations. The sizes of the NoL effect for CA group were 55 msec in word, *F*(1,20) = 6.15, *p* = .022, = .235, and 123 msec in pseudoword reading, *F*(1.20) = 16.13, *p* < .001, = 447. Unlike what was observed in lexical decision, those in the CA group responded more slowly (46 msec) to 6L3S than 4L2S words, *F*(1.20) = 7.79, p = .011, = .280. In regards to syllable manipulation, DYS responded 118 msec slower to 6L3S than 6L2S pseudowords, *F*(1.10) = 4.66, p = .057, = .317. The CA group did not present a response to NoS manipulation, *F* < 1. The influence of lexicality manipulation was on average 129 msec larger for the DYS than CA group, *F*(1.30) = 10.06, p = .003, = .251.

Response duration. Again, the three-way interaction of Group x Lexicality x Item Type was significant, *F*(2,29) = 4.85, p = .015, = .251, stemming from the NoL manipulation, *F*(1.30) = 6.74, *p* = .014, = .184, not from the NoS manipulation, *F* < .1. Figure 1B shows that the DYS group prolonged their responses in particular when reading six-letter pseudowords. Crucially, within-group analyses showed Lexicality x NoL interaction both in DYS, *F*(1.10) = 10.02, p = .010, = .501, and in CA groups, *F*(1.20) = 5.36, p = .031, = .211. With respect to NoS, the CA group articulated the 6L3S items 32 msec faster than 6L2S items, *F*(1.20) = 4.78, p = .041, = .193, whereas the DYS group articulated both type of words at equal speed, *F* < 1. The lexicality effect was 380 msec greater for the DYS, *F*(1,30) = 17.93, p < .001, = .374 than the CA group.

3.5 A Post-Hoc Study

The dynamics of phonological decoding was additionally studied with three dyslexic children (all third-grade 9-year old boys) in a local clinic serving those with learning disabilities. The children received the same naming task as specified in the Methods section, but with a mixed presentation of words and pseudowords. The general intelligence (WISC-III) of the participants was normal with performance IQs of 92, 100, and 88, and verbal IQs of 118, 97, and 96, while scoring -2, -3, and -2.3 *SD*s, respectively, in a standardized word list reading task (Lukilasse Graded Fluency Test; Häyrinen et al., 1999). The children were presented with the same naming task as specified in the Methods section, but with a mixed presentation of words and pseudowords. The average values are shown by black lines in Figure 2, along with the data of second-grade dysfluent readers presented by gray lines. The dyslexic readers began their naming responses earlier than second-grade dysfluent readers, but showed even more inflated response durations. There were no signs of manipulated effects in response onset times, but a strong length and small lexicality effect in response durations and summed onset and duration measures were observed. This small supplementary data suggests that the more severe the reading problem, the more the phonological decoding may be conducted online.

Figure 2 Naming data of three clinical third-grade dyslexics, when the presentation of words and pseudowords were mixed. For comparison, gray lines show the average values of second-grade dysfluent readers in the blocked naming task.



4 Discussion

The word reading processes of typical and dysfluent second-grade readers in the transparent Finnish orthography was assessed by studying the effects of different linguistic units (words, syllables, letters) in visual naming and lexical decision tasks. The partial correlation analysis, in which IQ was controlled for, revealed that lexicality, number of letters, naming measure, task, and word frequency effects were significantly correlated with reading fluency. All the correlations were negative, indicating that the smaller the influence of the studied effect (e.g. lexicality) the higher the reading fluency. The ANOVAs then revealed more fine-tuned information about the connection between reading fluency and studied effects.

In line with recent findings across transparent orthographies (De Luca et al., 2009, 2008; Di Filippo et al., 2006; Martens & de Jong, 2006, 2008; Zoccolotti et al., 2008), increased responses to length and lexicality manipulations were found among dysfluent readers both in naming and lexical decision tasks. The present study presents three important novel findings concerning dysfluent reading in a transparent orthography. First, dysfluent readers were slower than the control readers in the lexical decision task relative to the naming task. Second, dysfluent readers also showed a number of syllable effect in the lexical decision task, but not consistently in the naming task. Third, in the naming task both the response onset time and response duration were sensitive measures of stimulus properties. Interestingly, already in second grade at the age of eight, typical readers were not affected by the number of letters per se in a lexical decision task. There was a length effect between four-letter and bisyllabic six-letter words, but not between four-letter and trisyllabic six-letter words, the latter result indicating that a major developmental shift from letter-based serial decoding to parallel-letter processing has been achieved. As expected on the basis of more elaborate phonological decoding required in the naming task relative to the lexical decision task (Baayen et al., 2006; Balota et al., 2004; Frost, 1998), the word length effects in naming response onset times were present both when four-letter words were compared to bi- and trisyllabic six-letter words. There was a lexicality-by-length interaction in response durations, which may be due to ongoing phonological decoding during the response in a transparent orthography (Hutzler et al., 2005), or due to less fluent articulation of pseudowords than words (Seidenberg & Plaut, 1998).

Typical readers did not demonstrate the expected impeding effect of number of syllables in pseudoword reading, whereas in the word reading condition there was a facilitatory effect of number of syllables on the naming response duration. The number of syllable effect seems not to behave consistently across orthographies as suggested by our inspection of Italian naming data with adult subjects available in the web (LEXVAR: Barca, Burani, & Arduino, 2002). The Italian data shows a facilitatory effect for number of syllables when the number of letters remains constant. The magnitude of this effect was ~ 20 msec per syllable, the same size as a hindering letter effect. These finding are somewhat in contrast to other languages in which the impeding number of syllable effect have been found in pseudoword reading, including French (Ferrand, 2000; Ferrand & New, 2003), German (Stenneken et al., 2007), and English (Jared & Seidenberg, 1990) even in word reading (New et al., 2006). One explanation for this discrepancy may be that the linear number of syllable effects may be present in languages such as German, French, English and Italian (Pagliuga & Monaghan, 2010) which feature complexities in syllabification or in syllable-stress assignment. The Italian language resembles Finnish in a number of ways: Italian is an only slightly less transparent orthography than Finnish; it has strong syllable stress in speech and a rich morphology, albeit less complex than Finnish. However, in terms of syllabification and assigning syllable stress, Finnish is clearly simpler compared to Italian. Finnish syllabification is governed by two rules and the main syllable stress is denoted by a single rule (Karlsson, 1999), whereas in Italian at least four syllabification rules are required (Hall, 1974). In addition, approximately 20% of multisyllabic Italian words have an irregular syllable-stress pattern and need to be recognized via non-rule-based, lexical processing (Pagliuga & Monaghan, 2010).

It is possible that the syllable may serve some other function than serial decoding unit. Slowing initial-syllable frequency effects have been consistently reported in some regular orthographies as in Spanish (Carreiras, Ferrand, Grainger, & Perea, 2005; Carreiras & Perea, 2007) and in German (Hutzler et al., 2005). No syllable frequency effects have thus far been studied in Finnish, but recently Häikiö, Hyönä, & Bertram (2010) studied the role of the syllable boundary in reading with Finnish second -graders, in both the autumn and spring semesters. They manipulated the bigram frequency in the syllable boundary and measured eye movements during reading. A syllable boundary effect was observed in the autumn but not the spring term, suggesting that the syllable may be a relevant unit only when beginning to read in Finnish, which mirrors the results from a similar German developmental study (Gagl et al., 2010).

Finally, the number of syllable effect may not be related to syllables per se, but rather to the consonant structure of the words. According to Frost (1998), the fluent reader may first decode consonants (not necessarily in a serial fashion) to constrain the lexical search and conduct a detailed phonological coding of vowels only if necessary for lexical disambiguation or for reading aloud. The tendancy to process the trisyllabic items faster than the bisyllabics may indicate that syllabic parsing is easier for the former type of items. The Finnish syllabification rule of denoting a syllable boundary before a vowel - consonant sequence, fits most readily to short CV syllable, from which the trisyllabic six letter items typically consist of. Instead, applying the main syllabification rule to the bisyllabic six-letter items containing successive consonants requires more letters. In addition, when reading bisyllabic six-letter items, one must also apply the second syllabification rule of denoting a syllable boundary between vowels that do not constitute a diphthong.

In line with previous studies, the dysfluent reading was characterized by larger length and lexicality effects in the lexical decision task (Di Filippo et al., 2006; Martens & de Jong, 2006), and in the total naming response time(Figure 1). Compared to the results obtained from the naming tasks, dysfluent readers' response times in the lexical decision tasks were much more delayed than those from the control group. The large influence of the number of letters indicates that dysfluent readers decode even familiar words in a letter-to-phoneme manner. However, the large lexicality effect shows that if the decoding leads to activation in the phonological lexicon, the later phonological output processes are greatly facilitated. Finally, slow pseudoword reading also indicates slowness in decoding, as suggested by Bergmann & Wimmer (2008). Problems in decoding are apparent from a developmental perspective. In transparent orthographies, reading acquisition is based on decoding skills (Seymour et al., 2003) and the poor reading is initially characterized by slow decoding speed (Wimmer, 1996b).

Dysfluent children displayed a slowing influence of number of syllables in the lexical decision task, but this was not reflected on partial correlations. This discrepancy, along with individual profiles, suggests that it is only the poorest readers who, in addition to phonemic decoding, assemble the phonemes into syllables. According to Frost (1998) assembling letters into syllables may help poor readers attain lexical access. It is somewhat a mystery why the dysfluent group did not demonstrate a consistent syllable effect in naming task despite the substantial lexicality effect, indicating that lexical processing was already taking place. One explanation for this pattern of results may be that in the naming task the children were mostly engaged in producing a correct phonemic response. For this reason only partial lexical activation may have been obtained, while complete lexical recognition may have occurred even post-response. This possibility was supported also by the results of the post-hoc study, in which there was no influence of lexicality or number of letter or syllable manipulation present in naming response onset times, but a strong influence of number of letter and a small influence of lexicality manipulation in response durations.

The present results of continued decoding during the naming response in dysfluent readers suggest that the assembly and lexical processes can co-occur or even follow the naming response in a transparent orthography, in which distant letters in a word do not influence the pronunciation of early letters in the word (Hutzler et al., 2005). However, it seems that mere orthographic transparency is only a prerequisite for yielding such a reading strategy, as even severely impaired readers in Italian have not shown a reduced pseudoword length effect in naming response onset times as a sign of an online decoding strategy, despite identical methodology and task instructions (De Luca et al., 2009; Zoccolotti et al., 2008). However, possible evidence for online decoding in Italian is reported by Orsolini, Fanari, Cerrachio, & Famiglietti (2009). In their study responses read aloud were qualitatively classified as fragmented decoding or lexical recognition on the basis of pronunciation correctness. The results indicated that beginning and dyslexic readers produced more serially ordered separate pronunciations of sublexical parts of a word, whereas more advanced readers presented more holistic responses. One factor behind the pronounced online phonological decoding strategy in Finnish may be the way in which reading is taught in the first grade in Finnish schools. Children are explicitly taught to slowly articulate the word aloud according to syllables or letters. In this manner, children are able to decode every Finnish word, regardless of length. It seems plausible that when the words are not easily recognized, Finnish children return to this systematic decoding strategy that they were taught in school.

The present results suggest a limitation in number of letters for the silent assembly process, as short but not long pseudowords were silently decoded, evidenced by a growing group difference in response durations as a function of number of letters. This may be due to limitations of the phonological buffer, which can be seen as a working memory for the assembly process (Ziegler et al., 2003). By focusing on single letter-sound correspondences during articulation instead of generating full phonological code in the mind, the online decoding strategy may relieve demands on working memory. Moreover, the online decoding resembles the orthographic evaluation process suggested by Bergmann & Wimmer (2008), in which dysfluent readers check more carefully whether the initial lexical recognition they made is correct. Thus, poor readers may concentrate on single letter-sound correspondences during articulation for self-monitoring and avoiding mistakes.

Taken together, the present study shows that typical second-grade children show a capability for parallel-letter processing by age 8. However, rapid phonological coding of a word syllable or consonantal structure may still occur. Dysfluent readers seemed to decode even familiar words at a letter-phoneme level, even by sounding out the words in a phoneme-by-phoneme fashion, depending on the task difficulty. When complete lexical access was required, they additionally chunked the letters into syllables. The results indicate an incapability of parallel letter processing, slowness in decoding and additional problems in attaining lexical access for dysfluent readers in transparent orthographies.

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Appendix

List of experimental items:

Naming, words:

4L2S: lelu, pipo, naru, poro, rapu, sora, mopo, mato, kynä, lasi, sade, kala, juna, vene, kisa, mäki, susi, loma, meri, rivi, raja, veli, koti, valo, kivi, **6L2S:** koukku, munkki, nilkka, kurkku, kaivos, lautta, piippu, suihku, lamppu, kuoppa, mainos, patsas, rengas, verkko, kiekko, myrsky, puisto, kerros, leikki, vanhus, taivas, hammas, luonto, kirkko, kauppa, **6L3S:** seteli, pusero, pisara, kipinä, vasara, sipuli, peruna, kitara, veturi, meteli, kävely, puhelu, kamera, satama, kanava, ikkuna, mitali, tavara, enkeli, matala, paperi, kaveri, numero, mukava, tarina

Naming, pseudowords:

4L2S: heku, sito, salu, toso, sanu, kopa, lovo, rapo, pylä, jati, tame, jatu, tusa, seke, mila, pähi, luti, tova, sesi, lini, laha, resi, hopi, naro, pini, **6L2S:** jousku, kulkki, kiikka, sunkku, haipos, vausta, tiilpu, luisku, talppu, nuuppa, tainos, lattas, pentas, teekko, hiesko, kyysky, vuinto, pertos, reiski, nantus, malvas, jasmas, ruusto, niikko, launpa, **6L3S:** keveli, lutero, mikara, liminä, pavara, tiluri, kevuna, pikara, sepuri, hekeli, rätely, muselu, pahera, malama, japava, okkina, nirali, sapara, ankila, rakala, naseri, naveli, tupero, suhava, hapira

Lexical decision, words:

4L2S: hame, havu, latu, maha, tori, mehu, mono, muna, muru, namu, pomo, romu, räme, sumu, papu, vesi, talo, raha, kone, käsi, pora, kylä, levy, lumi, katu, **6L2S:** vaippa, veitsi, viitta, viikko, viesti, heikko, sääntö, käärme, miekka, hiekka, laukku, kaappi, toukka, keitto, kioski, kortti, kyltti, liekki, niitty, pensas, piikki, pultti, reitti, teltta, turkki, **6L3S:** kolari, lattia, ritari, tivoli, väline, salama, terävä, sokeri, sekava, kamala, ämpäri, kypärä, lokero, pipari, kotelo, hunaja, rypäle, majava, lakana, sopiva, vakava, sanoma, matala, ystävä, tarina,

Lexical decision, pseudowords:

4L2S: läte, junu, nalu, hepi, rano, lata, roje, pähi, vola, mykä, jery, ruvi, raku, pale, jatu, hapu, kaja, nosi, seku, romo, vuha, luvu, tasu, soko, kopu, **6L2S:** leisto, tooski, soltti, nyrtti, keekki, tiitta, tenpas, huikki, tuntti, leisti, kertta, sulkki, haappa, reetsi, piirta, seikko, kiesto, jeikku, läänti, täisme, vienka, leekka, sausku, taalpi, routka, **6L3S:** motero, tovake, voselo, ruhaja, kytäle, patava, sapana, rokiva, lapava, kaloma, rasala, ästivä, sapina, posari, sartia, linari, nitoli, närine, tanama, melävä, hoperi, lemava, parala, amperi, nykärä.

III

Dissociating spatial and letter-based word length effects observed in readers’ eye movement patterns

by

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Dissociating spatial and letter-based word length effects observed in readers' eye movement patterns

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Abstract

In previous eye movement research on word length effects, spatial width has been confounded with the number of letters. McDonald (2006) unconfounded these factors by rendering all words in sentences in constant spatial width. In the present study, the Arial font with proportional letter spacing was used for varying the number of letters while equating for spatial width, while the Courier font with monospaced letter spacing was used to measure the contribution of spatial width to the observed word length effect. Number of letters in words affected single fixation duration on target words, whereas words' spatial width determined fixation locations in words and the probability of skipping a word. The results support the existence of distinct subsystems for deciding where and when to move eyes in text (Rayner & McConkie, 1976). The number-of-letters effect in fixation duration may be explained by visual acuity, visual crowding, and/or serial letter processing.

Keywords: word length, number of letters, spatial width, eye movements, reading

1. Introduction

In eye movement research on reading, a standard finding is that word length influences both the time spent fixating a word and the amplitude of the saccade entering a word. Longer words are fixated for longer than shorter words (e.g., Calvo & Meseguer, 2002; Hyönä & Olson, 1995; Juhasz, White, Liversedge, & Rayner, 2008; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Sereno, & Raney, 1996; Underwood, Binns, & Walker, 2000). The bulk of the effect comes from an increased frequency to refixate a longer word. The increased refixation frequency in turn is likely to reflect constraints of foveal vision. When not all the letters of a word fit in the foveal area, a refixation is needed to compensate for visual acuity limitations (Vergilino-Perez, Collins, & Dòre-Mazars, 2004).

The amplitude of a saccade programmed to a long word is also greater than that to a short word. This is due to the reader targeting the word center (Rayner, 1979): in order to position a fixation around the word center (demonstrated to be the optimal viewing location for word perception, see e.g., Nuthmann, Engbert, & Kliegl, 2005; O'Regan & Levy-Schoen, 1983; Vitu, O´Regan, & Mittau, 1990), a longer saccade is needed than in case of a short word. Despite the lengthening of saccade amplitude as a function of word length, the initial fixation lands closer to the word beginning from the word center for long than short words (e.g., Bertram & Hyönä, 2003; the initial landing position in a word is called the preferred viewing location, Rayner, 1979).

That parafoveal word length information is acquired and utilized in reading is also evidenced by Inhoff, Starr, Liu, and Wang (1998) in a study exploiting the gaze contingent boundary technique, in which the to-be-fixated parafoveal word was manipulated during a saccade towards it. Correct length information (the parafoveal preview and the target word share the same number of letters) provided for the parafoveal word (*barcohqo* -> *movement*, i.e., the preview and the target are both eight letters long) speeded up the target word processing when it was subsequently fixated, compared to incorrect length information (*barc ohqo* -> *movement*; see also Inhoff, Radach, Eiter, & Juhasz, 2003; White, Rayner, & Liversedge, 2005).

Word length is also found to significantly affect the probability of skipping over a word: short words are skipped much more often than longer words (for a review, see Brysbaert, Drieghe, & Vitu, 2005). This finding reflects the fact that short words can be processed parafoveally more efficiently than longer words (Vitu & McConkie, 2000).

In most of these studies (if not all), a monospaced font (Courier) was used in presenting the experimental texts. A relevant feature of monospaced font is that each letter covers the same horizontal width. Thus, the number of letters in a word has a perfectly linear relationship with the word's spatial width. As a result, it is not clear to what extent the previously obtained word length effects reflect processing at the orthographic (an effect due to the number of letters) versus visual (an effect due to spatial width) level. In other words, it is not known whether the effects in refixation probability, saccade amplitude, and skipping probability are due to the number of letters per se, the word's spatial extent, or both.

McDonald (2006) was the first to investigate the independent contributions of number of letters and spatial width in the observed word length effect. In his study all words in the experimental sentences were rendered to cover an equal spatial width. Moreover, a set of 6- and 8-letter target words was selected that were matched for a number of lexical characteristics. In the target word analysis, a number-of-letters effect was observed in gaze duration (i.e., the time spent fixating a word before exiting it) and in the number of fixations. Gaze duration and number of fixations were greater for 8-letter than 6-letter words. However, saccade amplitude was not affected, as both the launch site and the landing position of the saccade entering the target word were unaffected by the number of letters; neither was the skipping probability. Most of these effects were replicated when the data for all words in the experimental sentences were analyzed using a repeated measures multiple regression technique. However, in this analysis the initial landing position (measured in letters rather than in pixels) in words moved rightwards as the number of letters increased. The number-of-letters effect in gaze duration and number of fixations is assumed to reflect orthographic processing, perhaps due to visual crowding (Bouma, 1970, 1973); individual letters of long words are harder to process than those of shorter words. The fact that there was no consistent number-of-letters effect in skipping probability or in initial fixation location suggests that saccades programmed across words are governed by the text's spatial attributes.

As a consequence of the rendering procedure employed by McDonald (2006), each word was written with a different font size. Moreover, as all words occupied exactly the same width on the computer screen, 10-letter words suffered from substantial visual crowding compared to 2-letter words. Finally, the results concerning saccadic programming were somewhat mixed between the two sets of analyses. Thus, more work is needed to dissociate the effects of the number of letters and spatial width from each other.

In the present study, the unconfounding of the effects of number of letters and spatial width was done in a natural way by using differences in fonts. The variability in letter width in proportional fonts enables a comparison of words with a varying number of letters but with an equal spatial width. In a proportional font such as Arial, a large variation exists in letter width (letter *m* is 2.5 times wider than letter *i*). Thus, in Arial the four-letter word 'mama' is wider than the six-letter word 'flight'. A comparison of these types of words provides an opportunity to examine the independent effect of the number of letters from that of the spatial width without the need to scale the font size separately for each word.

We selected short four- and six-letter words as targets for the following reasons. First, as they all fit in the foveal vision (± 1° around the fixation point) when fixated upon, observed effects are unlikely to stem from visual acuity constraints. Second, although six-letter Arial words are visually more crowded than four-letter words, they are less so than the 6- and 8-letter words used by McDonald (2006). Moreover, an effect of visual crowding may have been prevalent in McDonald's study, as his participants were untrained to read texts where each word is written with a different font size. In our study, on the other hand, the participants were free to make use of their natural, highly practiced reading habits developed for reading texts written consistently in the same font, which may additionally reduce crowding effects, as crowding is shown to be reduced by practice (Chung, 2007).

To also examine the extent to which spatial width contributes to word length effect, a spatially controlled number-of-letters effect (studied with Arial, as described above) was compared to a "standard" length effect obtained when reading 4- and 6-letter words written in monospaced font (Courier). The possible unique contribution of spatial width in saccade programming was further evaluated in a post-hoc analysis by comparing eye movements on target words written in proportional font (Arial), for which the spatial extent varied but the number of letters remained constant. Finally, the comparison of proportional and monospaced font both at the word and sentence level should reveal if there are inherent font differences in reading. In what follows, we discuss in more detail the issues addressed in the present study.

As noted above, word length effects frequently emerge in the probability of making a refixation on the word. An additional fixation on a word typically lengthens the gaze duration of this word by 200 ms or more (for a review, see Rayner, 1998). Some refixations are associated with difficulty in word recognition (Rayner et al., 1996; Vergilino-Perez et al., 2004), but most refixations are made to compensate for the acuity limitations of the foveal vision (Vergilino-Perez et al., 2004). Therefore, it is expected that in the present study refixations should be more frequent on monospaced six-letter words than other target words, as they cover more space than the other targets, extending slightly over foveal vision. Moreover, the results of McDonald (2006) suggest that number of letters may affect refixation probability even when the spatial extent is controlled for. If replicable, a difference in refixation probability (and gaze duration) should also emerge between our 4- and 6-letter target words equated for the spatial extent (i.e., written in Arial).

McDonald (2006) also observed a pure number-of-letters effect in the single fixation duration made on the word, suggesting that the number of letters may also influence temporal aspects of eye movement control, not only saccadic programming, as indexed by the effect in refixation probability. Other studies where the spatial extent was not controlled for have also found an effect of word length in first or single fixation durations (Kliegl et al., 2004; Rayner et al., 1996), although it has not been a constant finding (Hawelka, Gagl, & Wimmer, 2010; Joseph, Liversedge, Blythe, White, & Rayner, 2009). A pure number-of-letters effect is especially likely to appear in transparent orthographies (Ziegler, Perry, Jacobs, & Braun, 2001), such as in Finnish, the language used in the present study, in which spelling-to-sound correspondences are based on single graphemes.

It is also of interest to study the independent contributions of spatial width and number of letters in parafoveal word processing in reading. If number of letters affects the probability of skipping over a word, we should then find a difference in skipping rate between 4- and 6-letter words written in Arial. On the other hand, if word skipping is modulated by words' spatial extent, no such effect should emerge, as these target words are of equal width. This is also what McDonald (2006) observed. If so, we should find a difference between 4- and 6-letter Courier words: 4-letter words should be skipped over more frequently than 6-letter words. On the other hand, if both number of letters and spatial width influence skipping rate, an effect would also be present in Arial, accompanied by even a stronger effect in Courier.

Moreover, as noted above, readers extract word length information from parafoveal words that is subsequently used in foveal processing. However, on the basis of the previous evidence, it is not known whether the acquired length information is entirely based on the spatial extent, or whether also the number of letters is extracted from parafoveal words, independently of spatial extent. The findings demonstrating that readers extract orthographic and phonological information of the beginning letters from parafoveal words (see reviews of Hyönä, in press; Rayner, 1998) hints at the possibility that readers may also acquire specific number-of-letter information from parafoveal words.

The above prediction may be tested by examining so called parafovea-on-foveal effects (Kennedy, 1998; Kennedy & Pynte, 2005). They refer to effects where features of the parafoveal word affect the processing of the foveal word. These effects are considered to index parallel processing of two adjacent words. When applied to the present context, an effect of the number of letters of the parafoveal word on the processing of the foveal word would indicate that number-of-letter information of the parafoveal word is processed simultaneously with the processing of the foveal word. In previous studies where number of letters was confounded with spatial extent, a parafoveal-on-foveal word length effect was either not found (Kliegl, Nuthmann, & Engbert, 2006), was inconsistent (Hyönä & Bertram, 2004), or fixation durations were actually shorter on the foveal word when the parafoveal word was longer (an inverse parafoveal word length effect; Drieghe, Brysbaert, & Desmet, 2005; Kennedy, 1998; Kennedy & Pynte, 2005). As these studies used monospaced font, they may underestimate the influence of number of letters as longer words extend farther into the parafovea, thus suffering more from visual degradation. This may lead to a decision to leave the foveal word early, in which case parafoveal processing may be attenuated.

Recently, Miellet, O'Donnell and Sereno (2009) compensated for this degradation by magnifying parafoveal letters in order to increase their spatial resolution to match with the resolution of the foveal letters. The magnification also led to an increase in the spatial width of the parafoveal words. This manipulation did not improve parafoveal word processing. However, the manipulation results in inaccurate parafoveal word length information (in terms of spatial width), which may have downplayed the parafoveal processing benefit.

In the present study, parafoveal processing of the number-of-letters information was examined when the spatial extent was equated for 4- and 6-letter target words. If number-of-letters information is processed for the parafoveal target word in parallel with the processing of the foveal word, the duration of fixation prior to fixating the target word should be affected. If we are to find an inverse parafoveal word length effect (Drieghe et al., 2005; Kennedy, 1998; Kennedy & Pynte, 2005), the greater number of letters in the parafoveal word will lead to a shorter preceding fixation. On the other hand, it is also possible that when the spatial width is controlled, we may find evidence for more effortful parafoveal processing as a function of number of letters. If so, the preceding fixation prior to fixating the parafoveal word will be longer when the parafoveal word is longer.

Finally, visuo-spatial factors may influence how many letters are processed during a fixation. Morrison and Rayner (1981) manipulated the viewing distance to see whether more letters are processed at a closer viewing distance (for visual acuity scales as a function of viewing distance, see Geddes, McLean, McMonnies, & Woodward, 1966). Yet, viewing distance was not found to affect saccade amplitudes in letters, which led to the conclusion that letters are more important than visual angle in determining saccade amplitude. Also font type may exert general effects on saccadic programming as condensed letter spacing of proportional font may allow for more letters to be processed during each fixation relative to monospaced font. Studies using overall reading rate as the dependent measure have found an advantage for monospaced over proportional font in small font sizes, whereas with larger font sizes proportional font has a 5-% advantage over monospaced font (Arditi, Knoblauch, & Grunwald, 1990a; Mansfield, Legge, & Bane, 1996). Arditi, Knoblauch, and Grunwald (1990b) suggest that with larger font sizes the proportional font is read faster, as more letters fit in foveal vision, thus decreasing the number of eye movements required, whereas with small print sizes tight letter spacing produces crowding, which impedes reading. However, in these studies eye movements were not registered, so this conclusion remains somewhat speculative.

Recently, Rayner, Slattery, and Bélanger (2010) studied using the moving window technique to examine whether letter spacing of proportional and monospaced fonts influence saccade amplitude and the perceptual span in reading. Indeed, more fixations per word were made in monospaced than proportional font (i.e., saccades were on average 0.6 letters longer when reading proportional font), but the perceptual span in words was equal between the fonts. On the other hand, fixations were 10 ms longer in the proportional font. Due this trade-off between number of fixations and fixation durations there was no difference between the fonts in overall reading rate. However, there is previous evidence that large differences in the readability of the font do have an influence also on reading speed (Paterson & Tinker, 1947; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Slattery & Rayner, 2010).

In the present study, in addition to target word analyses, we also conducted sentence level analyses of reading monospaced (Courier) and proportional (Arial) font to examine whether font type influences any aspect of readers' eye movements. As both fonts are highly readable (for a review, see Josephson, 2008), no difference in reading speed was expected. The most interesting question in this analysis is whether the mean number of letters travelled during forward saccades differs between fonts, which would indicate a visuo-spatial influence on saccadic programming, and perhaps even on the perceptual span.

2. Materials and Methods

2.1. Participants

All the 35 university students (mean age of 23 years, SD=3 years) participating in the study were native Finnish speakers with no history of reading problems and normal or corrected-to-normal vision. The participants received a movie ticket as a reward for their participation.

2.2. Apparatus

An SMI HiSpeed eye tracker with 500 Hz sampling rate was used to record eye movements of the participants' right eye. The computer screen of 375 x 300 mm with a resolution of 1024 x 768 pixels was located at the distance of 640 mm from the participant's eye. At this viewing distance the center-to-center letter distance of 14 pixels corresponded to a visual angle of 0.459 º per letter (Table 1) equaling 2.17 letters per degree; for Courier New this was the exact value, while in Arial the angle varied depending on the letter – the mean letter width in the Arial sentences was 10.5 pixels equaling 3.05 letters per degree.

2.3. Materials

There were 30 four-letter and 30 six-letter target words in proportional-width Arial 18 pt font and 20 four-letter and 20 six-letter target words in monospaced Courier New 18 pt font[1] (see Appendix for the complete stimulus set). To control for the spatial width, four-letter proportional words were selected among the widest of four-letter words in a 17-

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[1] To ensure that the difference in the number of items between the fonts did not explain the findings, we recomputed the analysis by including only the first 20 four-letter and six-letter proportional words in the analysis. The pattern of results turned out to be highly similar.

million word newspaper corpus (Research Institute for the Languages of Finland, 2007). The four-letter words contained many wide letters such as ‘m’. Conversely, the six-letter words were selected from among the narrowest of six-letter words including many narrow letters, such as ‘t, r, i, l’. Matching for the spatial width in such a way is feasible in Finnish, in which narrow-letter word bodies, such as ’iitt’, are relatively frequent. Nonetheless, the pool of suitable words was very limited.

The four groups of target words (four- and six-letter Arial and Courier New words) were matched for surface word-form frequency (see Table 1 for group means). The four- and six-letter Arial and four-letter Courier New words were also matched for pixel width (Table 1), whereas the six-letter Courier New words were wider (81 pixels). All the words were common Finnish nouns appearing in the base form (i.e., non-inflected).

The target words in both fonts were presented in sentences, so that a four-letter Ariel word was paired with a six-letter Ariel word (the same was done with the Courier words), and a sentence frame was created that was identical at least up to the target word (Figure 1). The remainder of the sentence was either identical in each pair or was modified to fit with the earlier part of the sentence. There was no difference between the fonts in the number of letters in words surrounding the target words, either in the preceding (7.7 letters in both fonts) or the subsequent (6.3 letters in proportional and 6.1 letters in monospaced font) word. The mean number of characters per sentence was 47.1 (SD=4.5) and 45.9 (SD=3.7) and the mean number of words was 6.2 (SD=.83) and 5.8 (SD=.97) for the proportional and monospaced font, respectively. The two font conditions were presented in separate blocks; the order of blocks was counterbalanced across participants. The sentences within a block were presented in a fixed, pseudorandom order.

The effect of spatial width when the number of letters was controlled was studied in a post-hoc analysis. The proportional font data allowed us to study this question by dividing the words into wide and narrow based on their spatial width, resulting in a 7-pixel (half a letter) difference, while all the other word properties remained controlled.

Insert Figure 1 about here

Insert Table 1 about here

2.4. Procedure

Participants leaned their head on a forehead and chin rest. After finding a comfortable position a 13-point calibration procedure was run. The calibration was repeated between each block. The instruction for participants was: “Look at a fixation cross and press a mouse button to see a sentence. Read the sentence silently once through. When you have completed reading the sentence, press again a mouse button to see a yes-or-no question related to the sentence. Answer this question either by pressing the left (yes) or the right (no) mouse button”. After excluding one ambiguously phrased question, the accuracy in responding to the comprehension questions was very high (98.4 %). There were three practice trials prior to the experimental trials. The participants were instructed not to make head movements during the experiment. The sentences were adjusted on a single line so that the target word always appeared in a center location on the screen.

2.5. Eye movement data processing

Fixations were detected by the saccade-velocity–based algorithm developed by the manufacturer (SMI), using the saccade velocity threshold of 50 °/s and a minimum saccade duration of 15 ms (a saccade reaching an angular velocity of over 50 °/s typically has a duration longer than 15 ms, so this parameter did not restrict the detection of saccades). Fixations shorter than 50 ms (9.0 %) and longer than 1000 ms (0.3 %) were excluded. Two participants with a high proportion of short fixations (15 % and 40 %) were excluded from the analyses.

Three areas of interest were identified: the beginning part of the sentence, the target word including the preceding space, and the sentence end. The fixation was classified as a first-pass fixation only when the reader entered the target word directly from the sentence beginning after having read it for the first time. The dependent variables in the target word analyses included the following first-pass measures: As temporal measures, we used gaze duration, single fixation duration, first fixation duration and the duration of fixation prior to target word fixation. Spatial aspects of eye guidance were measured by the length of the saccade entering the target, the initial landing position on the target (including the preceding space), the probability of skipping the target, and the probability of refixating the target.

In the sentence level analyses the dependent variables included total fixation time and total number of fixations averaged over sentence, word and character, average fixation duration, probability of regression, and average saccade amplitude in pixels and letters (average letter width of 14 pixels for the monospaced font and 10.5 for the proportional font was used; the latter value was determined as the mean letter width in the proportional font sentences).

3. Results

3.1. Effects of the number of letters in the proportional and monospaced font

Table 2 presents the mean values for each eye movement measure for the four- and six-letter target words presented in the proportional and monospaced font. The temporal eye fixation measures showed no interactions between number of letters and font type, Fs < 1, but significant main effects of number of letters and font type. In gaze duration there was a significant main effect of font with Arial yielding a mean of 221 ms and Courier a mean of 205 ms, F(1,32)=16.72, p<.001, η_p^2=.343; moreover, the 11 ms effect of number of letters was also significant, F(1,32)=11.75, p = .002, η_p^2=.269. The same pattern of results was true for single fixation duration: the 15-ms main effect of font was significant, F(1,32)=26.00, p<.001, η_p^2=.448, as was the 8-ms number-of-letters effect, F(1,32)=5.57, p = .025, η_p^2=.148; and for first fixation duration: the 17-ms main effect of font, F(1,32)=24.71, p<.001, η_p^2=.436, and the 6-ms number-of-letters effect F(1,32)=7.71, p=.009, η_p^2=.194 were both reliable. The duration of the previous fixation showed a main effect of font with Arial yielding a mean of 191 ms and Courier a mean of 182 ms, F(1,32)=15.56, p<.001, η_p^2=.327, but there was no effect of the number of letters in the target word, F<1.

Spatial eye movement variables showed significant interactions between font type and length. For the initial landing position, the main effects of font, F(1,32)=153.9, p<.001, η_p^2=.828, and number of letters F(1,32)=22.17, p<.001, η_p^2=.409, were qualified by a Font x Number of Letters interaction, F(1,32)=32.22, p<.001, η_p^2=.502. The number-of-letters effect (0.6 letters) was significant in the monospaced font, F(1,32)=34.26, $p < .001$, η_p^2=.517, where the increase in the number of letters was accompanied by a corresponding increase in spatial extent, but not in the proportional font, F(1,32)=1.84, p=.185, η_p^2=.054, where the spatial extent was identical for the four- and six-letter words.

The amplitude of the entering saccade showed a main effect of font, F(1,32)=415.7, $p<.001$, η_p^2=.929, but not of number of letters, F(1,32)=1.71, p =.199, η_p^2=.051, nor a Font x Number-of-Letters interaction, F<1. Initial saccades were on average 30 pixels longer in Courier New than in Arial. The font effect disappeared when the mean pixel values were transformed into mean values in letters, F<1. Thus, when reading Courier New text, the eyes have to make longer jumps to reach the preferred viewing location in words than when reading Arial text. A more puzzling finding is that the effect of spatial extent seen in the initial landing position in the monospaced font was not present in the initial saccade amplitude. For some reason, the eyes appear to be launched from a somewhat farther distance in the four-letter than six-letter Courier words.

For the skipping probability there was no main effect of font, F<1, whereas the main effect of number of letters F(1,32)=35,14, $p <.001$, η_p^2=.523, and the Font x Number of Letters interaction, F(1,32)=34.40, $p<.001$, η_p^2=.518, were highly significant. In the monospaced font, four-letter words were skipped for 21.4 % of the time, whereas six-letter words only for 3.6 % of the time, F(1,32)=40.20, $p < .001$, η_p^2=.557.In the proportional font the average skipping rate was 13.9 % , but there was not even a hint for a length effect, F<1. Moreover, four-letter monospaced words were skipped more frequently (21.4 %) than four-letter proportional font words (14.1 %) F(1,32)=7.34, p=.011, η_p^2=.187, whereas for the six-letter words the skipping percentage was 3.6 % for monospaced, and 13.6 % for proportional font words, F(1,32)=24.00, p<.001, η_p^2=.429.

To examine whether the skipped words were identified and whether the repetition of the sentence frames (the same sentence frame was used twice, once including a four-letter and once including a six-letter target word) influenced skipping (Reichle, Pollatsek, & Rayner, 2006), the trials resulting in target word skipping (439) were categorized into four groups: whether or not a regression was launched to the target word and whether the sentence frame was presented for the first or second time. If the target word skipping is followed by a regression back to it, it may be taken as evidence that the word was skipped without fully identifying it (Vitu & McConkie, 2000). The trials were distributed quite evenly across the four categories: first presentation of sentence frame with no regression, 25 %, second presentation with no regression, 24 %, first presentation with a regression, 23 %, and second presentation with a regression, 28 %. As skipping occurred equally often in sentence frames presented for the first or second time, it is unlikely that readers tried to guess the target words as a result of a familiar sentence beginning. The regression rate was radically increased for skipped (51 %) compared to non-skipped (24 %) target words (see also Vitu & McConkie, 2000). This seems to indicate that some of the words were skipped before fully recognizing them.

Finally, the probability of refixating the target word revealed two marginal effects, a marginal main effect of number of letters F(1,32)=3.12, p =.087, η_p^2=.089, and a marginal Font x Number of Letters interaction, F(1,32)=2.94, p=.096, η_p^2=.084; the main effect of font was non-significant, F<1. These marginal effects reflect the trend of refixating more often six-letter (9.9 %) than four-letter (6.6 %) words in the monospaced font.

Insert Table 2 about here

3.2. The effect of spatial width when the number of letters is controlled

The target word analysis suggests that saccade targeting may be governed almost solely by spatial information. If this is the case, spatial width of words may affect reading independently from the number of letters. The proportional font data allowed us to study this question further by dividing the Arial words into wide and narrow ones based on their spatial width, resulting in a 7 pixel (half a letter) difference. More specifically, the results reported in Section 3.1. suggest that the initial landing position would be adjusted according to spatial width. Moreover, narrower words may be skipped more frequently than wider words, whereas wider words may be refixated more frequently than narrower words. Table 3 presents the means and significance levels of the analyses of variance for the spatial measures involving spatial width as a within-participants factor.

The spatial measures were consistently affected by spatial width. Narrow words were fixated two pixels closer towards the word beginning than wide words, F(1,32)=6.71, p=.014, η_p^2=.173, which corresponds to 0.16 letters when number of letters was used as the measure, F(1,32)=4.61 p=.040, η_p^2=.126. The initial saccade amplitude was 3 pixels shorter for saccades executed into narrow than wide words, F(1,32)=4.79 p=.036, η_p^2=.130, which was not significant when measured in number of letters, F=1.88. The strongest effect was observed in skipping rate, which indicated that narrow words were more frequently skipped

(17.2 %) than wide words (10.6 %), F(1,32)=20.80, p<.001, η_p^2=.394. Thus, it is the spatial width, not the number of letters that governs the decision of whether or not to skip a word. Finally, differences between the words were apparently too short to produce a width effect in refixation probability, F<1.

Insert Table 3 about here

3.3. Sentence level analyses

Table 4 presents the means of sentence-level eye movement measures for reading proportional and monospaced font. Average fixation time per sentence, F(1,32)=3.02, p=.092, η_p^2=.086, per character, F(1,32)=.564, p=.458, η_p^2=.017, and per word, F(1,32)=1.29, p=.263, η_p^2=.039, showed no overall font difference; neither did number of fixations per sentence, F(1,32)=1.52, p=.676, η_p^2=.006, or per character, F<1, whereas more fixations per word were made in reading monospaced (1.74) than proportional font (1.63), F(1,32)=10.98, p=.002, η_p^2=.256. Out of all fixations, 25 % were regressions, but there was no difference between the fonts in the percentage of regressions, F(1,32)=2.16, p=.151, η_p^2=.063. However, consistently with the target word analysis, average fixation duration was 8 ms shorter in reading monospaced than proportional font, F(1,32)=16.80, p<.001, η_p^2=.344. Finally, average forward saccade amplitude was larger in monospaced than in proportional (111 vs. 82 pixels) font when measured in pixels, F(1,32)=944, p<.001,

η_p^2 =.967, but not when measured in mean number of letters, F(1,32)=1.190, p = .283, η_p^2 =.036, as on average 7.87 letters was progressed during a saccade in both fonts.

Insert Table 4 about here

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4. Discussion

The present study provides important new insight about the word length effect standardly observed in readers' eye movements, by dissociating from each other the effect of the number of letters and that of spatial width. This was achieved by taking advantage of variation in letter width in proportional font, enabling a comparison of four- and six-letter words with equal spatial width. The spatially controlled word length effect was then contrasted with the "standard" word length effect obtained with monospaced font, where an increase in the number of letters coincides with a corresponding increase in spatial extent. Effects of the number of letters and word's spatial extent were examined both in spatial and temporal eye movements parameters.

Similarly to McDonald (2006), saccade programming, as indexed by the amplitude of the saccade entering the target word and its landing position, was determined by spatial width but was not affected by the number of letters. Also the probability of skipping over four- and six-letter words was determined by their spatial width, but not by the number of letters. Effects of spatial width in saccade programming were also observed in an analysis comparing these eye movement measures for wide and narrow four-letter proportional-font words. Finally, there was a marginal trend to refixate more often six- than four-letter monospaced words; in addition, the sentence-level analysis revealed that more fixations per word were made in monospaced than proportional font. These findings are in line with the view that the text's spatial attributes are the primary force in saccade programming during reading. Number-of-letter information appears to be play no role, at least when targeting saccades to shorter words. This pattern of results provides novel support for the view that the decisions of where and when to move the eyes are being made independently from each other, as originally suggested by Rayner and McConkie (1976).

As noted above, skipping probability was governed by spatial width and not affected by the number of letters (see also McDonald, 2006). The percentage of skipped six-letter monospaced words was only 3.6 %, while that of four-letter monospaced words was 21.4%. In the comparison of wide and narrow Arial words, the skipping probability was found to increase by one percent per pixel. Such a dependency on mere spatial width but not on the number of letters is likely to be related to visual acuity constraints of the foveal vision. The further into the parafovea a word extends, the less likely it is that letter identity information necessary for word identification may be gleaned from the outmost letters. The supplementary analysis of skipping trials provided evidence for the view that some skipped words were not fully identified prior to skipping (see also Vitu & McConkie, 2000), as more regressions were being launched to skipped than non-skipped words. Word skipping is likely to result partially from oculomotor error leading to saccadic overshoot and possibly lead to its subsequent correction by a regression targeted to the skipped word.

There was also a font difference in skipping probability, as four-letter monospaced words were skipped more often than four letter proportional words (14.1% and 21.4 % of trials, respectively). This is surprising as these words had equal spatial width. This finding may at least partially be explained by the presence of horizontal Serifs (semi-structural details at the ends of strokes) in the monospaced Courier New font. When the outer Serifs are removed, the average pixel width drops by five pixels equaling the width of narrow Arial words, and also the skipping probabilities are more alike (21.4 % for four-letter Courier and 17.2 % for four-letter narrow Arial words). Nevertheless, the four-percent difference suggests that also some other visual factors than mere spatial width may contribute to skipping probability at small visual angles. One potential explanation is a crowding effect between words, as spaces between words in proportional font are narrower than in monospaced font. Wider word spaces have been found to have beneficial effects on reading with small print sizes (Arditi et al., 1990a, 1990b; Drieghe et al., 2005; Rayner, Fischer, & Pollatsek, 1998). Specifically, visually well distinguishable, short parafoveal words in monospaced font may be easier to recognize, which would show up in increased skipping rate. Finally, it should be noted that monospaced four-letter words were slightly more frequent than four-letter proportional font words, which may also contribute to the observed difference (for a review of word skipping, see Brysbaert et al., 2005).

With respect to general font effects, our results are largely in line with those of Rayner et al. (2010): There was no overall font difference in reading time, average fixation duration was longer for proportional font, and more fixations per word were made in monospaced font. In contrast to Rayner et al. (2010), however, it was not found that more letters would be traversed during each saccade when reading monospaced than proportional font. This discrepancy may be due to a methodological difference, as we did not measure how many letters was traversed during each saccade, but average saccade length in pixels was divided by average letter width - a procedure which may have underestimated local text influences on saccade programming. Our finding of no effect of letter spacing on saccade amplitude in letters, a small effect found by Rayner et al. (2010), and the findings that parafoveal processing is not affected by letter spacing (Rayner et al., 2010) or spatial frequency of the parafoveal letters (Miellet et al., 2009) all support the view that the perceptual span is mainly attentionally (Morrison & Rayner, 1981) rather than visuo-spatially (Arditi et al., 1990b) limited. Font effects in fixation durations may be accounted for by a slightly increased visual processing load during reading of proportional font. The Arial and Courier New fonts differ from each other not only in letter spacing, but also in stroke width and presence of Serifs, so no strong conclusions about the exact source of this font difference can be made (Mansfield et al., 1996).

In contrast to saccade targeting, fixation time measures were influenced by the number of letters. In gaze duration, first fixation duration and single fixation duration there was a genuine word length effect not modulated by font type, which supports the view that number of letters is an important factor in governing the fixation time on foveally inspected words, at least in transparent orthographies (Ziegler et al., 2001) such as Finnish, the language studied in the present experiment. The lack of a parafoveal-on-foveal effect (i.e., target word length did not influence the duration of the preceding fixation) suggests that the number-of-letters effect was restricted to fixated words, which is consistent with the view that attention is allocated serially between words in reading (Reichle, Pollatsek, Fisher, & Rayner, 1998).

As regards temporal measures of eye movements, we obtained a small but reliable number-of-letters effect in gaze duration (11 ms), in first fixation duration (6 ms) and in single fixation duration (7 ms). The small effect size may be explained by the fact that these differences were observed between short, four- and six-letter words. The effect size is smaller than that obtained by McDonald (2006) for six- and eight-letter target words (a difference of 20 ms in gaze duration and a linear increase of 6 ms per letter in single fixation duration). The effect in gaze duration is in line with previous studies, in which the effect is caused by more frequent refixations on longer words (e.g., Hawelka et al., 2009; Joseph et al., 2009: Rayner et al., 1996). The length effect in single fixation duration appears to be somewhat at odds with previous studies conducted in monospaced font. Hawelka et al. (2010) did not find a word length effect among three- to seven-letter words in single fixation duration. Neither did Joseph et al. (2009) find a length effect in first fixation duration between four- and eight-letter words, nor did Hyönä and Olson (1995) for words ranging from 5 to 11 letters. The absence of a number-of-letters effect in first fixation duration may be due to the fact that the first fixation is often followed by a refixation on the word, resulting in a reliable word length effect in gaze duration.

In the two most prominent eye guidance models (E-Z Reader, Reichle et al., 1998, 2006; SWIFT, Engbert, Nuthmann, Richter, & Kliegl, 2005) a word length effect in fixation duration and refixation rate stems from the effort required for letter encoding dependent on the eccentricity of the letters from the center of the fovea. The further away a letter is, the more difficult it is to recognize. If the letters are too far to be encoded, a refixation is made. The temporal length effects in monospaced font may be explained by this visual acuity account. The spatial extent of six letter monospaced words exceeded slightly the span of foveal vision, so letter encoding of the outmost letters may have required extra time, thus producing the effect in single fixation duration. Also, a refixation was sometimes required, presumably for visual acuity reasons (Vergilino-Perez et al., 2004).

However, an explanation based on visual acuity cannot account for the number-of-letters effect obtained for spatially controlled proportional font words. We propose two alternative accounts for this effect, one based on visual crowding and another based on serial letter processing. McDonald (2006) suggests that visual crowding (Bouma, 1970, 1973) may be responsible for the spatially controlled word length effect obtained in single fixation duration. He scaled words horizontally to an equal spatial width of 2 visual degrees, so that the longest words (a maximum length of 10 letters) were compressed, thus suffering from noticeable crowding, while the shortest words (a minimum of 2 letters) were expanded in size, which was likely to reduce an effect of crowding to a minimum. However, crowding was much less dramatic in the present study than in the McDonald study, as words were presented in their natural appearance (i.e., no scaling was carried out).

According to Levi, Klein, and Hariharan (2002), foveal crowding occurs only at the edge-to-edge distance of shorter than 1/6 of the center-to-center distance of adjacent letters, which corresponds to 2.3 pixels with the typical 14-pixel center-to-center letter distance in both fonts used in the current experiment. The closest-edge letter spacing in both fonts was typically 2-3 pixels. For many letters (e,u,o,p,a,s,m) there is not a big difference in letter spacing between the fonts used in the present study (i.e., Arial: euopasm, Courier New: `euopasm`). However, for some letters in the Courier New font (`itlj)` the closest-edge distance is much greater than in Arial, where these letters have a closest edge distance of only 1 pixel (itlj). The last set of letters were frequent in our six-letter Arial and four-letter Courier words, so it is fair to say that inter-letter spacing was sparser in the monospaced font. Moreover, according to Liu and Arditi (2000), narrow letter spacing may produce letter confusion between some letters: The point-of-spread function imitates the actual visual image of the retina, which is somewhat blurred. When inter-letter spacing decreases, some letters tend to merge together in this blurred picture. With very short inter-letter spacing, for example the letter string ‘JJ’ may be sometimes recognized as ‘JU’. Taken together, foveal crowding provides a reasonable explanation for spatially controlled number-of-letters effect in single fixation duration observed in the present study.

Another explanation for the number-of-letters effect is offered by the dual-route model of word recognition (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). In this model word recognition is seen as a net result of the workings of the sublexical and lexical routes. The sublexical route operates by converting graphemes to phonemes working serially from left to right, thus producing a number-of-letters effect. On the other hand, the lexical route processes all letters in parallel and maps the letter cluster onto an orthographic word representation; thus, no length effect is produced by this route.

In transparent orthographies, such as Finnish, the correspondence between graphemes and phonemes is regular, so the grapheme-phoneme conversion (GPC) route can always provide a correct pronunciation. Accordingly, phonological influences on word recognition (Katz & Frost, 1992) as well as the word length effect (Ziegler et al., 2001; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003b) are pronounced in transparent orthographies (but see Hawelka et al., 2010). Computational simulations of the dual route model suggest that a transparent orthography may lead to faster working of the GPC route, thus allowing the serial process to contribute more to word recognition (Ziegler, Perry, & Coltheart, 2003a). The number-of-letters effect in fixation time may be explained by this view, as we obtained a persistent number-of-letters effect in a completely transparent orthography (Finnish), even when the words were so short that their processing was not constrained by the limitations of the foveal area.

The above view is also advocated by Wydell, Vuorinen, Helenius, and Salmelin (2003), who detected a word length effect between four- and eight-letter words in a functional neuroimaging study conducted with Finnish-speaking participants. Wydell et al. suggested that the serial letter-to-phoneme conversion may be a permanent part of reading orthographically transparent languages such as Finnish (however, see Adelman, Marquis, & Sabatos-DeVito, 2010, for recent evidence for parallel processing of letters in English).

It was also of interest to examine whether the word length effect is present during parafoveal processing of target words. However, no such effect was detected, as the duration of fixation prior to fixating the target word was practically equal between four- and six-letter proportional font words. This result appears to be at odds with the findings of an inverse effect of parafoveal word length (i.e., the fixation prior to fixating a long word is shorter) obtained in monospaced font (Drieghe et al., 2005; Kennedy, 1998; Kennedy & Pynte, 2005). The length manipulation in these studies was more robust than in the present study, so it seems possible that the inverse parafoveal word length effect may reflect an effect of spatial width rather than an effect of the number of letters.

In conclusion, by comparing word length effects in reading text in proportional font (where an increase in the number of letters may not necessarily widen the word’s spatial extent) and monospaced font (number of letters and spatial extent co-vary) we found that in the transparent Finnish orthography saccades are programmed solely on the basis of words’ spatial width, whereas fixation durations are affected by the number of letters. The number-of-letters effect obtained in fixation duration may be explained by visual acuity, visual crowding, serial letter processing, or a joint influence of all three factors.

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Appendix (Target Words)

The sequence of target words with corresponding English translations in the parentheses:

Proportional font: karkki (sweet), pupu (bunny), tontti (slot), mato (worm), pultti (bolt), kortti (card), ansa (trap), tulkki (interpreter), muru (bit), muta (mud), leikki (play), maja (hut), pesä (nest), turkki (fur), kana (chicken), home (mould), keitto (soup), mopo (moped), tankki (tank), maha (belly), torttu (tart), maku (taste), teltta (tent), nuha (flu), viitta (cape), meno (plan), muna (egg), kyltti (sign), aamu (morning), loitsu (spell), romu (scrap), pomo (boss), kaisla (reed), mono (ski boot), reitti (route), hymy (smile), kuitti (receipt), niitty (field), saha (saw), veitsi (knife), silkki (silk), namu (candy), leivos (cake), mehu (juice), laitos (facility), vintti (attic), hana (tap), nenä (nose), voitto (victory), hame (skirt), kontti (container), liekki (flame), ahma (wolverine), kioski (kiosk), vilkku (blinker), räme (marsh), sumu (mist), piikki (spike), puhe (speech), linkki (link)

Monospaced font: ilta (night), hammas (tooth), juna (train), kala, (fish), kaivos (mine), kauppa (shop), kesä (summer), kerros (floor), kynä (pen), kiekko (puck), kirkko (church), lasi (glass), latu (trail), koukku (hook), kurkku (cucumber), lelu (toy), lamppu (lamp), meri (sea), lautta (ferry), mainos (advertisement), myrsky (storm), mäki (hill), naru (rope), palo (fire), pipo (cap), patsas (statue), poro (reindeer), raja (border), rapu (crab), piippu (chimney), sade (rain), sora (gravel), puisto (park), rengas (tire), suihku (shower), susi (wolf), taivas (sky), vene (boat), vanhus (oldie), verkko (net)

Figure caption

Figure 1. A sample sentence in the two fonts. The Arial sentence translates literally into English as follows: ‘Prepared from its own ingredients a *juice* / *soup* has the best taste’, with the words in italics corresponding to the Finnish word ‘mehu’ and ‘keitto’, respectively. The Courier New sentence translates literally into English as follows: ‘Dropped to the floor the *glass* / *lamp* broke down loudly’.

Table 1

Table 1. Descriptive Statistics of Target Words Including the Mean Values for Word Frequency (Per Million Words), and Width in Pixels and in Visual Angle, with Standard Deviations in the Parentheses.

	Monospaced		Proportional			
	Courier New		Arial			
	Four	Six	Four	Six	Narrow	Wide
Word freq[1].	15.2	15.4	7.1	8.0	6.7	8.3
	(12.9)	(26.7)	(9.4)	(16.8)	(12.2)	(14.8)
Width (pixels)	53*	81	52.8	51.3	48.7	55.4
			(3.4)	(4.5)	(2.2)	(2.1)
Visual angle (degrees)	1.73	2.65	1.73	1.68	1.59	1.81

*=48.05 (2.45) when outer serifs are removed.

[1] Words were common Finnish words. Due to hundreds of inflected word forms of the same base word, surface word frequencies are typically lower in Finnish than in English. The frequency of monospaced words were slightly higher, which may explain why font main effects in fixation times tended to be larger in target word analysis compared to sentence level analysis.

Table 2

Table 2. Mean Values for First-Pass Eye Movement Measures for the Number of Letters Effect in the Proportional and Monospaced Font, Standard Deviations in the Parentheses.

	Proportional Arial		Monospaced Courier New	
Measure	Four-letter	Six-letter	Four-letter	Six-letter
Gaze duration	216 (28)	225 (34)	199 (29)	212 (39)
Single fixation duration	205 (24)	214 (34)	192 (28)	198 (35)
First fixation duration	206 (23)	212 (32)	189 (28)	195 (34)
Previous fixation duration	190 (24)	192 (30)	182 (27)	181 (31)
Skipping probability	.141 (.144)	.136 (.140)	.214 (.195)	.036 (.062)
Refixation probability	.080 (.065)	.076 (.045)	.066 (.060)	.099 (.088)
Initial landing position, in pixels	35 (5.1)	34 (5.4)	43 (7.2)	52 (9.3)
Initial landing position, in letters	3.35 (.48)	3.24 (.51)	3.09 (.52)	3.71 (.66)
Initial saccade amplitude, in pixels	90 (16)	91 (24)	119 (24)	121 (16)
Initial saccade amplitude, in letters	8.57 (1.53)	8.70 (1.85)	8.47 (1.70)	8.65 (1.17)

Table 3

Table 3. Mean Values and Level of Significance of First-Pass Eye Movement Measures for the Effect of Spatial Width When Number of Letters was Controlled by Using a Proportional Font; Standard Deviations Are Presented in the Parentheses.

Measure	Narrow	Wide
Skipping probability	.172 (.171)	.106 (.112) **
Refixation probability	.076 (.066)	.079 (.055)
Initial landing position, in pixels	33.7 (5.66)	35.5 (4.46) *
Initial landing position, in letters	3.22 (.54)	3.38 (.43) *
Initial saccade amplitude, in pixels	88.7 (14.7)	92.4 (20.1) *
Initial saccade amplitude, in letters	8.52 (1.46)	8.76 (1.94)

* = p < .05; ** = p <.001.

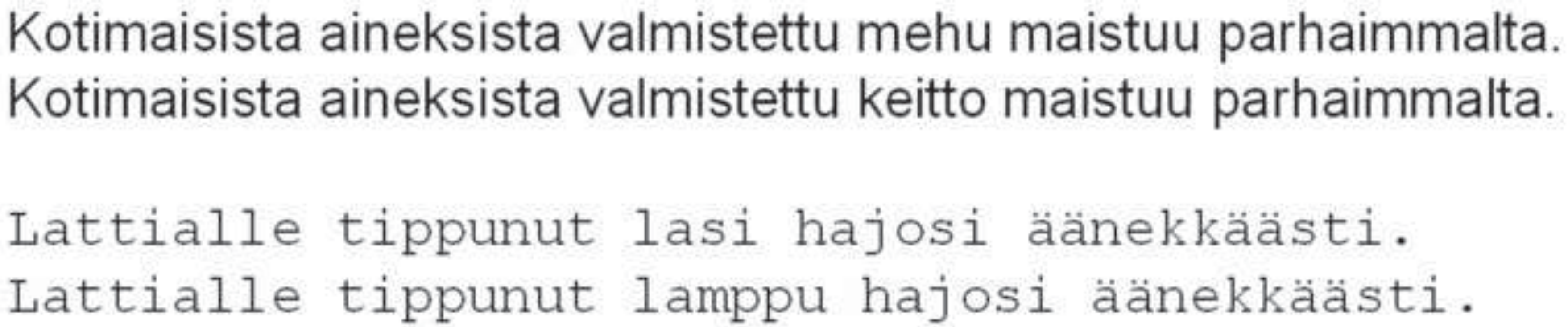
Table 4

Table 4. Mean Values and Significance Levels for the Sentence-Level Eye Movement Measures in Reading Proportional and Monospaced Font; Standard Deviations Are in the Parentheses.

Font type	Proportional Arial	Monospaced Courier New
Fixation time per sentence	2028 (366)	1940 (359)
Fixation time per word	332 (61)	343 (63)
Fixation time per character	43.3 (7.9)	42.5 (7.9)
Number of fixations per sentence	9.90 (1.7)	9.85 (1.5)
Number of fixations per word	1.63 (.28)	1.74 (.25)*
Number of fixations per character	.21 (.04)	.22 (.03)
Regression percentage	24.6 (6.7)	25.5 (7.0)
Forward saccade amplitude in letters	7.84 (1.18)	7.91 (1.09)
Forward saccade amplitude in pixels	82.3 (12.3)	110.7 (15.3) **
Average fixation duration	205 (23)	197 (24) **

* = $p < .05$; ** = $p < .001$.

Figure 1



Kotimaisista aineksista valmistettu mehu maistuu parhaimmalta.
Kotimaisista aineksista valmistettu keitto maistuu parhaimmalta.

`Lattialle tippunut lasi hajosi äänekkäästi.`
`Lattialle tippunut lamppu hajosi äänekkäästi.`

IV

Orthographic uniqueness and deviation points in fluent and dysfluent adult readers in a transparent orthography

by

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Manuscript

Orthographic uniqueness and deviation points in fluent and dysfluent reading in a transparent orthography

(5700 words)

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Abstract

The influences of serial orthographic word uniqueness, pseudoword and nonword deviation points were examined in lexical decision tasks both with fluent and dysfluent readers, in the fully transparent Finnish orthography. Experiment 1, with fluent adult readers, showed no word uniqueness point effects, but found clear pseudoword deviation point effects located at the syllable boundary. Experiment 2 extended to dysfluent reading the null-effect of the word uniqueness point and the impeding pseudoword deviation point effect. In addition, a facilitatory nonword deviation point effect was observed in both reader groups. The dysfluent readers showed generally slower response times, were more distracted by the pseudowords, and showed trends towards greater pseudoword and nonword deviation point effects relative to fluent readers. The results with fluent readers provide support for the dual-route view of reading in transparent orthographies, and hint at a special role for the initial syllable in lexical searches within the serial reading procedure. Dysfluent readers seem to have established functional whole-word recognition, but remain somewhat slower in phonological decoding.

Keywords: lexical decision, orthographic uniqueness point, neighbors, syllable

1 Introduction

A fundamental question in visual word recognition research is whether the processing of letters is serial or sequential at some level of cognitive processing. In cross-linguistic studies, researchers have found smaller lexical-semantic influences (for a review, see Katz & Frost, 1992) and more recently a larger word length effect (number of letters) (Ziegler, Perry, Jacobs & Braun, 2001; Ziegler, Perry, Ma-Wyatt & Schulte-Körne, 2003) in transparent orthographies. These orthographies have a more straightforward correspondence between graphemes and phonemes than is found with opaque orthographies, which have a comparatively complex correspondence between graphemes and phonemes. The explanations offered for these findings involve serial conversion of graphemes to phonemes (Ziegler, Perry & Coltheart, 2003), or special processes related to multisyllabic word recognition (Álvarez et al., 2000). In the present study the hypothesis that lexical search is serial was addressed by systematically studying the effects on visual lexical decision response times of orthographic word uniqueness points (Kwantes & Mewhort, 1999) and nonword deviation points (Lindell, Nicholls & Castles, 2003).

The present study was conducted in the fully transparent Finnish orthography. In addition to orthographic transparency, there are also other factors that favor the serial processing of words in Finnish. The agglutinative structure of Finnish words often allows a single word to contain several morphological endings (e.g. takka^{1}a^{2}mme^{3}kin^{4}ko^5 = *also*^{4} *to*^{2} *our*^{3} *fireplace*^{1}*?*^{5}). Finnish is also rich in terms of compounding (e.g. musta^{1}viini^{2}marja^{3}mehu^4 pullo^5 = *a bottle*^{5} *of black*^{1}*currant*$^{2\ and\ 3}$ *juice*^{4}*)*. These types of words routinely require serial intra-word processing (Hyönä, Laine & Niemi, 1995). Inflections also affect the word stem, as in the case of (taking a syllabified example) lam-pi *(pond)* vs. lam-men *(pond's),* and even affect the syllabification itself, as in tak-ka (*fireplace*) vs. ta-kan (*fireplace's*) (see Karlsson, 1999). Furthermore, on the basis of findings on inhibitory initial syllable frequency effects, Àlvarez et al. (2000) and Carreiras et al. (2005) have suggested that the syllable may be an important unit for lexical access among multisyllabic words. Nearly all Finnish words are multisyllabic, but syllabification in Finnish is governed by a couple of simple rules, and in speech the initial syllable of a word always receives primary stress (Karlsson, 1999). All these factors call into question the validity of word units as wholes, making the rapid phonological coding of visual words on the basis of either letters or syllables a possibility to be reckoned with in Finnish.

In our earlier eye movement study, a small word-length effect of 5 ms per letter was obtained for the fixation durations of target words during silent sentence reading (Hautala, Hyönä & Aro, 2011). However, being tied to the physical properties of the stimuli, the word-length effect may result from low-level perceptual factors, including visual and articulatory preparation processes (Seidenberg & Plaut, 1998). Moreover, although the word-length effect in response times gives an indication of the amount of processing taking place per letter, it is not a direct measure of whether this processing is serial or parallel.

Nor is the word length effect a measure of the actual lexical recognition, that is, of the selection of the correct lexical representation. On the other hand, if reading is serial, the beginning of the word – in words of equal length – should be more important for the lexical activation than the ending of the word. As hypothesized within the dual-route framework (Coltheart et al., 2001), this may be due to early letter sequences in a word being sooner available for phonological lexical search than late letter sequences, or to word initial letters having greater weight in lexical search within the orthographic lexicon (Álvarez, Carreiras & de Vega, 2000; Carreiras, Ferrand, Grainger & Perea, 2005). Serial processing in visual word recognition is even more apparent in developmental dyslexia, as evidenced by a substantially pronounced word length effect in transparent orthographies, one that is also apparent in lexical decisions (Di Filippo, De Luca, Judica et al., 2006; Juphard, Carbonnel, & Valdois, 2004; Martens & DeJong, 2006). The predominant interpretation of these findings has relied on a dual-route view of reading (Coltheart, Rastle, Perry et al., 2001), to the effect that dyslexics have difficulties in establishing a whole-word procedure involving the processing of letters in parallel, and that they consequently rely mainly on the serially operative grapheme-phoneme conversion route (Zoccolotti et al., 2005; Martens & DeJong, 2008). Alternative views suggest that dyslexics have problems in visuo-spatial attention (Bosse, Tainturier, & Valdois, 2007) or suffer from an excessive degree of visual interference from nearby objects (Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009), in other words visual crowding (Bouma, 1970). However, only a few studies using transparent orthographies have been conducted with adult dyslexics (Moll, Hutzler & Wimmer, 2005; Hawelka, Gagl & Wimmer, 2010). The results of these studies suggest that the word length effect in dyslexic reading may not be as pronounced in adulthood as it is in childhood.

The *uniqueness point* (UP) is an index of the informativeness of the word beginning. It refers to the letter position at which a letter string resolves into a unique word in a language. This means that no other word has that particular word beginning; hence in principle, processing letters after the uniqueness point is unnecessary for lexical disambiguation. For example, the Finnish word *kissa (cat)* has a UP value of 3, as there are words such as *kirja (book)* sharing the two initial letters, but no other five-letter word begins with the syllable *kis-*. Thus, in principle, for lexical disambiguation, the remaining two letters are irrelevant.

Currently, a hindering influence of the UP on response times has been reported in relation to naming (Kwantes & Mewhort, 1999; Lindell, Nicholls, Kwantes & Castles, 2005) and in lexical decision tasks (Lindell et al., 2003), but not in studies of readers' eye movements (Miller, Juhasz & Rayner, 2006). Interestingly, Lindell et al. (2003) introduced a nonword analogue for the word uniqueness point in a lexical decision task, termed the *nonword deviation point* (DV). The nonword deviation point refers to the letter position after which the letter string can no longer be a word. Contrary to the authors' expectations, this effect was found to be a facilitatory one – the more an item resembled a real word, the faster it was decided to be a nonword. The author suggested an explanation based on the LEX model of word recognition (Kwantes & Mewhort, 1999). According to LEX and the word superiority effect (Baron & Thurston, 1973), in the context of a valid word beginning, the letters that do *not* fit with the expected word are more reliably and more rapidly encoded. By contrast, when the invalid letter occurs early in the item, the model predicts a prolonged search in the lexicon, with checking on whether the letter was encoded correctly. The positive findings of uniqueness and deviation points in word recognition suggest that lexical search is serial (for an alternative view, see Lamberts, 2005). However, since the work of McClelland and Rumelhart (1981), the letter processing of words has been thought to be conducted in parallel (Adelman, Marquis & Sabatos-DeVito, 2010; Inhoff, Pollatsek, Posner & Rayner, 1989; Coltheart et al., 2001). In Dual Route model of reading aloud (DRC; Coltheart et al., 2001) nonwords are read by the serial route. As a result, the lexical search for nonwords from the phonological lexicon may also be conducted serially, predicting an inhibitory deviation point effect for nonwords. In our own case, we stood by the prediction made according to DRC, despite a facilitatory effect found by Lindell et al. (2003), on the grounds that the explanation offered by Lindell et al. may be more valid in English orthography, where word recognition is known to be more driven by lexical competition (Ziegler et al, 2001; 2003); this would presumably be due to the fact that grapheme-phoneme associations do not provide such reliable information as they do in transparent orthographies.

2 Experiment 1

Our first study investigated pseudoword deviation point and word uniqueness point effects in fluent Finnish readers in a lexical decision task. A consequence of the parallel processing of letters is that neighboring words – that is, those words derived by replacing one letter – are thought to be the ones most likely to be activated initially (McClelland &Rumelhart,1981). However, initial syllable frequency has been repeatedly shown to have an impeding influence on word recognition in (transparent) Spanish orthography (Àlvarez et al., 2000: Carreiras et al., 2005), presumably due to a mechanism such that more frequent initial syllables activate a larger number of word neighbors. I propose that a serial search of lexical items within a neighborhood may be a potential cognitive mechanism for the special role of word beginning and initial syllables for lexical search. For this reason, uniqueness point values were calculated also within a word's *neighborhood.* Our definition for a word's neighbor-UP is the last letter position in which the word has a neighboring word. For example, *kynsi (nail)* has a neighbor-UP value of 2, because it has a neighbor *kansi (cover)*, but no neighbors in later letter positions. In contrast with the uniqueness point, the neighbor-UP is compatible with the view prevailing since McClelland and Rumelhart (1981), to the effect that the *ending* of a word also constrains the lexical search. Thus, in reading a word like *kynsi*, the *-nsi* ending prevents the activation of non-neighbor words with a *ky-* beginning, such as *kyllä* (yes) and *kylmä* (cold). On the other hand, if the syllable (Alvarez et al., 2000; Carreiras et al., 2005) is an important unit in a lexical search, the present study should show a clear effect depending on whether the letter string is disambiguated at the initial or at the second syllable.

2.1 Material and Methods

2.1.1 Subjects

The participants consisted of 24 native Finnish-speaking university students (18 females, 6 males) with a mean age of 21 years (standard deviation 1.5 years) and with normal reading skills.

2.1.2 Equipment

The lexical decision task was administered by the Cognitive Workshop program running on a standard laptop computer.

2.1.3 Procedure

For each trial, a white cross in the middle of a black screen was shown for 750 ms, followed by a blank screen for 250 ms, after which the experimental item appeared. The task was to decide whether the item was an existing Finnish word or not, by pressing a left (word) or a right (pseudoword) keyboard arrow button. The item was presented in 48 pt Arial font, with each letter corresponding roughly to one visual angle at the 50 cm viewing distance. The items remained on the screen until a response was registered. A blank screen appeared for 1000 ms between each trial. All the words and pseudowords were randomly presented for each subject, interposed with a brief pause in the middle of the experiment.

2.1.4 Materials

The stimuli consisted of 150 pseudowords and 150 words. First of all, 30 common five-letter nouns, such as *kissa (cat)* with no or as few as possible neighbor words were selected. A letter was then changed in each position (1 to 5) for each of these words, yielding 150 pseudowords conforming to Finnish phonotactics; for example, the word *tyttö* (girl) formed the basis for the following pseudowords *nyttö, tättö, tyntö, tytkö, tyttä.* The bigram frequency based on a 17 million-word newspaper corpus (Kotus, 2007) was equal among the five classes of pseudowords. As suggested by Lamberts (2005), the number of neighboring words was also controlled for, based on a subset corpus of five-letter words that had a word frequency of over two occurrences in a million words (Kotus, 2007). However, the pseudowords constructed by changing letter position 3 had on average one more neighbor than other classes of pseudowords (see Table 2). The 150 words consisted of the base words for the pseudowords, plus an additional 120 words. Subsets of words with different uniqueness points but with equal word frequency and an equal number of neighbors were selected for use in uniqueness point analyses.

For uniqueness and deviation point calculations, the subset corpus was first arranged alphabetically. Thereafter, the letter position for which there was no basic form word sharing the same word beginning was assigned to each experimental item. The neighbor-UP was calculated by manually going through the neighboring words determined by the Neighborhood Watch program (Davis, 2005). A value for the last letter position of a word that also had a neighbor was given to each experimental item. The item properties and mean response times are presented in Tables 1 and 2.

2.1.5 Data processing

Out of the 7500 trials, 208 (2.8 %) were responded to incorrectly, and 190 (2.5 %) were responded to at either a slower or faster rate than 2.5 standard deviations from the subject means. These two classes of trials were excluded from the analyses, as were the data from three words – *kanne* (lawsuit), *kouru* (groove) and *kuomu* (hood) – that deviated from average reaction times (> 745 ms).

2.2 Results

2.2.1 Word uniqueness point

There was no main effect of UP for letters, either in participant analysis, F(2.22)=.028, p=.972, η_p^2 =.003, or in item analysis, F<.010. The respective average response times across participants, for UPs in the third, fourth, or fifth letter position were as follows (standard deviations in parentheses): 605 (70) ms, 603 (63) ms, and 604 (67) ms.[1]

2.2.2 Pseudoword deviation point

The effect of the pseudoword deviation point was highly significant, both in participant analysis, F(2.22)=34.16, p=.000, η_p^2 =.756, and in item analysis, F(2,79)=10.59, p<.001, η_p^2 =.196. Items resolving into pseudowords at the third letter position had response times of 649 (86) ms, whereas items resolving at the fourth and fifth letter positions had response times of 686 (91) ms and 688 (96) ms, respectively.

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[1] Note that the RT values presented in Tables 1 and 2 are averages per item.

TABLE 1 Item properties, mean response times per item (RT), and standard deviations (SD) for word uniqueness and pseudoword deviation points. The abbreviations are: letter position (P), number of items (Nr), word frequency per million words (WF), number of neighbor words (N), and bigram frequency per thousand words (BG). The horizontal dotted line represents the position of the syllable boundary.

	Word uniqueness point					Pseudoword deviation point				
P	Nr	WF	N	RT[1]	SD	Nr	BG	N	RT[1]	SD
2-3	27	22.4	2.41	606	43	30	8.04	1.43	649	27
4	27	16.4	2.18	606	47	30	8.39	1.23	688	41
5	27	17.3	2.70	606	52	30	9.07	1.13	689	44

Note: [1] Surface word frequency values are generally low in Finnish due to the large number of different word forms for the same base word.

2.2.3 Word neighbor uniqueness point

There was no main effect of neighbor-UP, either in participant analysis F(2.22)=.338, p=.683, η_p^2=.034, or in item analysis, F<.1. The respective response times for those words with a neighbor-UP at the third, fourth and fifth letter positions were as follows (standard deviations in parentheses): 601 (69) ms, 599 (62) ms and 604 (66) ms.

2.2.4 Pseudoword neighbor deviation point

Although there was no main effect of neighbor-UP either in participant analysis, F(4.92)=1.55, p=.194, or in item analysis, F<.1, the contrast between the response times for the first (672 ms) and last (685 ms) letter positions was at the borderline of significance, F= 4.291, p=.050, η_p^2 =0.157. There was also a significant difference between the items resolving into pseudowords at the initial (674 ms) or second (684 ms) syllable, F=4.98, p=.036, η_p^2 =0.178, but this did not emerge as significant in item analysis, F=1.60, p=.207.

TABLE 2 Item properties, mean response times per item (RT), and standard deviations (SD) for the word neighbor uniqueness point (UP) and pseudoword neighbor deviation point (DP). The abbreviations are: letter position (P), number of items (Nr), word frequency per million words (WF), number of neighbor words (N), bigram frequency per thousand words (BG). The horizontal dotted line represents the position of the syllable boundary.

Word Neighbor UP						Pseudoword Neighbor DP					
P	Nr	WF	N	RT	SD	P	Nr	BG	N	RT	SD
						1	30	8.92	1.33	673	35
						2	30	7.55	1.20	674	41
1-3	40	15.3	2.85	603	49	3	30	8.44	2.33	678	49
4	40	13.9	2.90	602	48	4	30	9.42	1.33	683	38
5	40	17.0	3.50	606	45	5	30	9.07	1.13	686	43

2.3 Summary of results for Experiment 1

There was a robust 40 ms effect for the pseudoword deviation point, and a weak 10 ms trend for the pseudoword neighbor deviation point, both of these being apparent at the syllable boundary between the third and fourth letter. There were no indications of a uniqueness or neighbor uniqueness point effect for words.

3 Experiment 2

In the second experiment, dysfluent and fluent Finnish readers were compared in a lexical decision task, with investigation of the word uniqueness point, pseudoword, and nonword deviation point effects. If the results of Experiment 1 were replicated, one could anticipate that there would be no word uniqueness point effect, but that there would be an impeding pseudoword deviation point effect. In addition to pseudoword deviation point manipulation, nonword deviation point manipulation was conducted by replacing either the first or last letter in a Finnish word with a foreign letter. The rationale for this manipulation was that the foreign initial or final letters would work as orthographic cues which might be detected early in the processing (Coltheart et al., 2001; McClelland & Rumelhart, 1981), thus preventing detailed phonological decoding or lexical search. It was thus expected that nonwords would be responded to more quickly than words or pseudowords, and because of the assumed parallel encoding of letters at the orthographic processing stage (Coltheart et al., 2001; McClelland & Rumelhart, 1981), no nonword deviation point effect was expected. Dysfluent readers tend to show generally delayed response times. If dysfluent readers have impairments in whole-word recognition, and as a consequence, read by a serial grapheme-phoneme conversion procedure, one could expect an impeding word uniqueness point effect along with a clear pseudoword deviation point effect. We were also interested in whether the dysfluent readers would show a nonword deviation point effect; this would indicate seriality already at the early orthographic processing level, such as in letter encoding.

3.1 Methods

3.1.1 Subjects

The participants were 35 native Finnish-speaking persons aged 16–36. They were recruited by sending an invitation letter via email to all secondary and higher schooling institutions in the Jyväskylä region. The email contained a link to an enrollment internet page, including questions involving possible exclusion criteria for concurrent eye movement research, these consisting of an eyeglass correction factor over 2 (which we have found to interfere with pupil and corneal reflex detection in eye tracking) and an age of below 15 or over 40 years. Following enrollment, a screening task for reading fluency was conducted via the internet, consisting of reading a single sentence and deciding whether it made sense or not (Luksu; Suokas, 2008). The participant's score was the number of correctly answered sentences within a one-minute time limit. Applicants belonging to the weakest fifth percentile – measured according to the distribution for young adults as registered in a large-scale Finnish twin study (Kaprio, 2006) – were considered to be potential dysfluent readers, and received an invitation to the study. Individuals performing two scores over this criterion were invited as potential control subjects. The screening procedure was approved by the ethical committee of the University of Jyväskylä.

The reading skill of participants was assessed by the Assessment Battery for Reading Disabilities in Young and Adults (Nevala, Kairaluoma, Ahonen et al., 2007), out of which subtasks for standardized Word reading, Pseudoword reading and Text reading were administered. The IQ of participants was assessed by Raven's Standard Progressive Matrices (Raven, Raven, & Court, 1998), this procedure being completed without time limit. In addition, participants were given tests involving Rapid Automatized Naming, Rapid Alternating Series and a Finnish version of the spoonerism task, the Phonological manipulation test. Table 4 presents the participants' performance in these tasks along with the results of independent sample t-tests between groups.

A participant was considered to be a dysfluent reader if he/she had a result belonging to worst at 11 percentage in population standards either in the Text or Word reading tasks. A participant was considered to be a fluent reader if he/she had results above the worst 11 percentage points of population standards in all of the reading tasks; this led to the exclusion of one subject who performed at a low level in the Pseudoword reading task. Because of a drastically poorer performance in Raven (score 39), one subject was excluded from the analysis. In addition, data from one subject was lost due to technical problems, leading to a total of 32 subjects in this study.

TABLE 4 Demographic Data on Age, Reading and Related Skills, and Cognitive Ability for Fluent and Dysfluent Reader Groups.

	Fluent (N=20)		Dysfluent (N=12)		t-test	
	Mean	SD	Mean	SD	t(30)	p
Age years	19.35	3.99	24.41	5.99	-2.87	.007
Raven SPM, score max 60	54.10	3.67	52.83	4.45	.873	.389
Word list, time in sec	22.66	5.17	36.04	6.03	-6.66	.000
Psword list, time in sec	42.96	8.93	69.22	13.99	-5.83	.000
Text reading, words in 3 min	362.3	36.07	296.0	22.44	5.71	.000
Word list accuracy	99.3%	.01%	97.7%	.03%	1.72	.109
Pseudoword accuracy	88.7%	.08%	81.1%	.12%	1.62	.122
Text reading accuracy	99.3%	.74%	98.9%	.58%	1.42	.166
Piglatin, correct max 15	11.75	3.53	8.83	5.30	1.69	.109
RAS, time in sec	28.65	4.19	39.36	8.99	-3.88	.000
RAN, time in sec	36.05	6.44	40.68	8.37	-1.72	.096

3.1.2 Equipment

The lexical decision task was administered by the E-Prime 1.0 program running on a standard desktop computer. The subjects leaned on the forehead rest and chin rest of an eye tracking column at a viewing distance of 67 cm. In addition to the mouse button response times, eye movements were registered. However, only response times are reported here.

3.1.3 Procedure

At the beginning of each trial a black cross on a white screen was shown for 1000 ms, after the experimental item appeared. The cross and the words always appeared at the same location: horizontally in the middle of the screen, and vertically at 25% from the upper frame of the screen. The participants' task was to decide whether the item was an existing Finnish word or not, as registered by pressing the left or the right mouse button. The correctness/incorrectness of the mouse buttons was balanced across subjects. Written instructions were given, and the button-pressing was practiced in eight trials before the start of the experiment. In order to control the spatial width of the words, the item was presented in monospaced 24 pt Courier New font with each letter corresponding to .57 visual degrees. The item remained on the screen until a response was registered. A blank screen appeared for 1000 ms between the trials. Items of different length were presented in separate blocks, balanced across participants. Short pauses intervened, with recalibration of the eye tracker. The presentation order of the items within a block was randomized separately for each subject.

3.1.4 Materials

The stimuli consisted of 240 pseudowords and 240 words (nouns) with an even number of five-, six-, and seven-letter items. There were 80 five-letter and 80 six-letter words; each set contained 20 early and 20 late uniqueness point words, controlled for frequency and number of neighbors. The words contained no foreign letters that would lead to a decrease in the sublexical familiarity of the words. (See Table 4 for descriptive statistics of the stimulus words.) The uniqueness point calculation was based on length-specific subsets from a large newspaper corpus (Kotimaisten kielten tutkimuslaitos, 2007), and the neighbor words and statistics were calculated by the Neighborhood Watch program developed by Davis (2005). On this occasion, the more-than-two occurrences in a million words criterion was not applied, in order to ensure that the uniqueness point values were correct even when very low frequency words were taken into account. Uniqueness point manipulation was attempted also with seven-letter words, but ultimately this was not considered reasonable, due to the redundant endings of long words in Finnish – for example *'mans**ikka**'* (strawberry) and *'mustikka'* (blueberry) – which led to a lack of variability in the uniqueness point.

The stimulus words provided the basis for the generation of pseudo- and nonwords: First of all, the words were divided into five groups of equal frequency, each containing 16 words. The pseudowords with early and late deviation points were constructed by replacing either the first or last letter in a word with a Finnish letter, in such a way that a phonotactically valid Finnish pseudoword was formed. The nonwords were constructed in a similar manner, but the replacement-letter was chosen from foreign consonants (q, w, d, f, g, z, x, c, b). In addition, one group of words was turned into random consonant strings for the purpose of the concurrent eye movement study. The response times for these consonant strings were substantially faster than those for the other types of item.

TABLE 3 Item properties of word uniqueness and pseudoword deviation points. The abbreviations are: number of items (Nr), word frequency per million words (WF), number of neighbor words (N).

	Nr	WF	N
Early	40	11.0	1.55
Late	40	8.5	2.25

3.1.5 Data processing

Out of the total of 16320 trials, 547 (3.3 %) were responded to incorrectly. In addition, 429 trials (2.6 %) were responded to with either a slower or faster response time than 2.5 standard deviations from the subject mean. These two trial classes were excluded from the analyses.

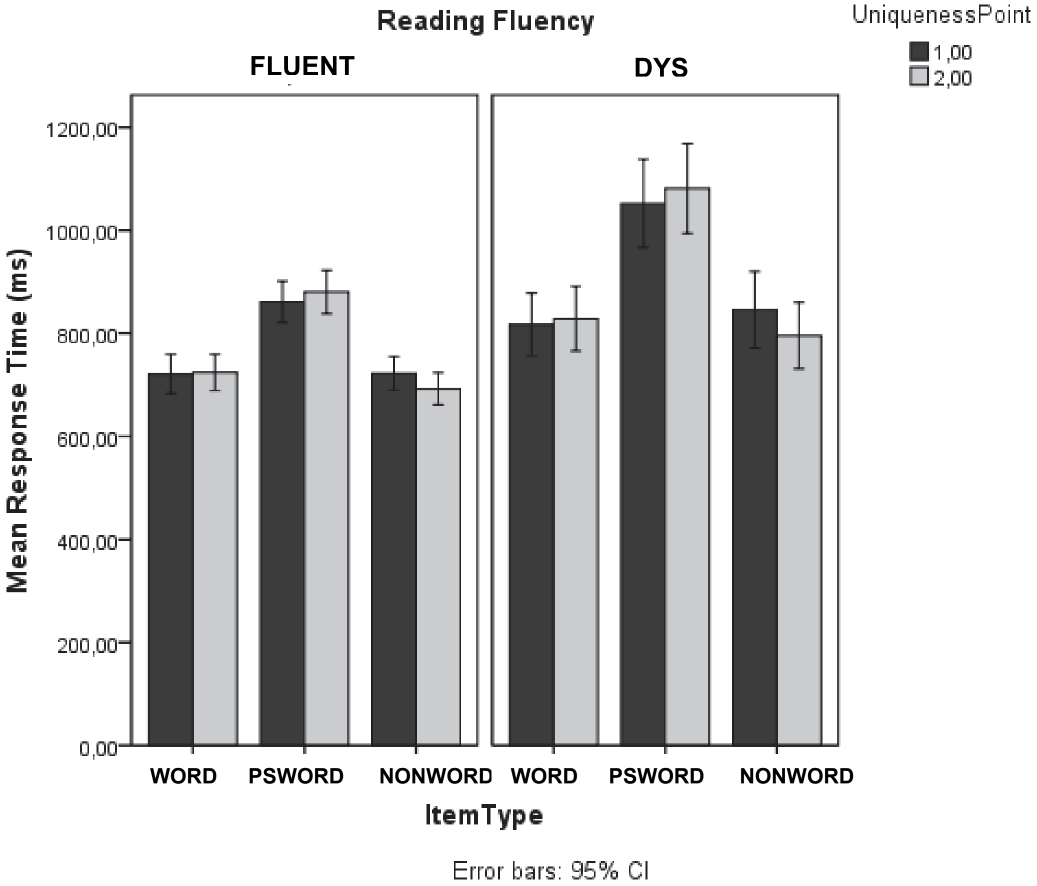
3.2 Results

Figure 1 shows the mean response times for dysfluent and fluent readers for the word uniqueness, pseudoword, and nonword deviation points. The results were analyzed by a repeated measures analysis of variance. This included a three-level within-subject factor of item type (words, pseudowords, nonwords), and a two-level within-subject uniqueness/deviation point factor (early, late). Reading fluency (fluent, dysfluent) was included as a between-subject factor.

There were significant main effects for Item type, F(2,29)=127.78, p<.001, η_p^2=.898, and Group, F(1,30)=6.05, p=.020, η_p^2=.168. However, the main effect of the uniqueness/deviation point, F<1, was not significant. The interaction between Item type and uniqueness/deviation point was highly significant, F(2,30)=32.11, p<.001, η_p^2=.517, since the uniqueness/deviation point effect was larger for pseudowords than for words or nonwords. There was no uniqueness point effect for words, F<.1. The Group x Item type interaction was significant, F(2,30)=4.25, p=.024, η_p^2=.227, reflecting the delayed response times of dysfluent readers to pseudowords, F(1,30)=3.23, p=.083, η_p^2 =.097. By contrast, this difficulty was not present in responses to nonwords, F=.001.

There was also a weak but significant three-level interaction of Group x Item type x Uniqueness/Deviation point, F(2,30)=3.87, p=.037, η_p^2 =.114. In separate ANOVAs there were trends for the pseudoword deviation point to be larger for dysfluent readers (31 ms for the fluent group vs. 70 ms for the dysfluent group), F(1,30)=3.25, p=.082, η_p^2 =.098. This was also the case for the nonword deviation point (− 32 ms for fluent, and − 60 ms for the dysfluent group), F(1,30)=2.26, p=.143, η_p^2 =.070, but it was clearly not the case with words, F<.5.

FIGURE 1 The influence on lexical decision response times of the word uniqueness point, and the pseudoword and nonword deviation points, among fluent and dysfluent adult readers.



3.3 Summary of results for Experiment 2

The results of Experiment 2 replicate the null effect of the word uniqueness point and also the impeding pseudoword deviation point effect (both observed also in Experiment 1). In addition, a nonword deviation point effect was demonstrated. In line with Lindell et al. (2003), the effect was a facilitory one; hence nonwords with late deviations from words received quicker response times.

The results for dysfluent readers confirmed our prediction of generally slower response times. Interestingly, pseudowords were the most challenging type of item for these subjects. There was also a trend towards an increased pseudoword deviation point effect, but this was clearly not present in real words. Dysfluent readers also showed a weak trend towards a larger facilitory nonword deviation point effect.

4 General Discussion

The impeding effect of the pseudoword deviation point observed in both experiments suggests that the lexical search for pseudowords is conducted serially. In Experiment 1, the effect was realized at the syllable boundary, which would suggest that the search is not conducted letter-by-letter, but rather dominated by the initial syllable (cf. Álvarez et al., 2000). However, because stimuli with a homogenous syllable structure were used in the present study, more research is required in order to resolve whether the pseudoword deviation point effect is triggered by a certain number of letters, or by an initial syllable compliant with a common word in a language. In contrast with the above, it should be noted that our manipulation of the orthographic uniqueness point of real words was not successful in producing any effect; this observation would support the prevalent view that the letters of a word are processed in parallel, and that all the letters contribute equally to a lexical search in the orthographic lexicon (Coltheart et al., 2001; McClelland & Rumelhart, 1981). The nonwords were responded to much more quickly than the pseudowords, and the late-deviating nonwords were responded to more quickly than the early-deviating nonwords (Lindell et al., 2003). As will be suggested, both of these findings may reflect the orthographic nature of the manipulation in question.

The dysfluent readers showed a pattern similar to the fluent readers, albeit with generally delayed response times. The null effect of the word uniqueness point would suggest that they have established a functional whole-word procedure, one that merely seems to operate rather more slowly than for typical readers. However, dysfluent readers showed trends towards larger impeding pseudoword effects, and larger facilitatory nonword deviation point effects, suggesting some remaining (though slight) inefficiency in phonological decoding.

There was no word uniqueness point effect, either within the neighborhood or entire lexicon. In principle, these observations can be understood in two ways. First of all, from the serial processing perspective, in a lexical decision task a word needs to be read to its very last letter in order to make sure that the item is not a nonword. Strictly speaking, this would make the uniqueness point useless when making lexical decisions for real words. However, given that words showed response times that were approximately 50-80 ms faster than those for pseudowords, the view that words are subject to more prolonged serial processing than pseudowords seems implausible. A more likely explanation is the prevalent view (Coltheart et al., 2001; McClelland & Rumelhart, 1981), to the effect that the letters of real words are processed in parallel.

Our null result for the uniqueness point is in contrast with the inhibitory effects found in lexical decision and naming tasks conducted in English (Kwantes & Mewhort, 1999; Lindell et al., 2003: 2005). Slightly longer items of 7-8 letters were used in these studies. Longer words may be subject to increased serial processing (e.g. in Finnish: Bertram & Hyönä, 2003) due to the visual acuity limitations of human vision, since acuity is precise only within two degrees of the visual angle from the center of the fixation point (Rayner, 1998). As refixation is needed for reasons of visual acuity, the reader may have more time to make use of an informative word beginning, which may lead to shorter refixation. However, no such evidence was found in the eye movement study conducted by Miller et al. (2006).

Our results indicating no influence of lexical disambiguation at the initial or final syllables in Finnish is to some extent in contrast to the well-reported findings regarding syllabic frequency effects on visual word recognition in another transparent orthography with clear syllable boundaries, namely Spanish (e.g. Álvarez et al., 2000). This potentially interesting cross-linguistic difference is supported also by Häikiö, Hyönä and Bertram (2010) , who studied the influence of rare bigrams at the syllable boundary on the eye movements of developing Finnish readers. They found an effect only in the younger group of readers; this would support the view that syllables are functional reading units only for the phonological route in Finnish orthography (which is notable for its transparency).

In addition, the finding regarding the inhibitory pseudoword deviation point is divergent from the facilitatory pseudoword deviation point effect found in an English lexical decision study (Lindell et al., 2003). The authors in this case suggested that in English it is easier to detect a non-existent word ending than a beginning, and that the non-existent beginning may actually trigger a prolonged lexical search. This explanation is understandable in the light of findings that lexical similarity such as rhymes plays a larger role in reading in an opaque orthography such as that of English, relative to transparent orthographies (Ziegler et al., 2001; 2003).

Despite the above, a closer look at the items used in present study and in Lindell's (2003) study reveals potentially important differences in manipulations used. Lindell and colleagues replaced the first two or last two letters in their nonwords (which are, in fact clearly pseudowords); however, in the present study only the first or last letter was replaced. Consequently, at least to a foreign reader (the first author), Lindell's pseudowords do not produce obvious lexical associations. The response times, too, provide support for this possibility. In Lindell's study, the words and pseudowords received similar response times, whereas in the present study the response times for the pseudowords were substantially longer than for the words and nonwords, which for their part were of similar magnitude. Thus it seems reasonable to assume that our very word-like pseudowords elicited stronger lexical activation than the pseudowords used by Lindell et al. (2003). Finally, Lindell's pseudowords, and the nonwords used in the present study both produced facilitatory deviation point effects; hence it would seem reasonable to compare these findings with each other than to compare our pseudoword deviation point effect to Lindell's nonword deviation point effect.

There may in fact be two cognitive mechanisms contributing to the facilitatory nonword deviation point effect. In the first place, the nonwords constructed by replacing a final letter in Finnish words violated the Finnish phonotactic expectations more heavily, and thus led to illegal bigrams at the end of a word, e.g. *kinkkx*. By contrast, the first letters in a word often resulted in a pronounceable loan-word type beginning, e.g. *dattu*. These kinds of nonwords would quite possibly receive a prolonged lexical search relative to items with an "illegal" ending. According to the word-superiority effect, letters are recognized more quickly from a word than from a letter string (Baron & Thurston, 1973). Applied to the present study, illegal letters in an item may be recognized more quickly, depending on how quickly it has been possible to stimulate the lexical activation of the item. If one assumes that in the present study a pseudoword beginning (as opposed to an end) was more powerful in producing lexical activation, it may be that the word-like beginning of nonwords could also have been beneficial for the detection of foreign final letters.

The dysfluent adult readers showed a surprisingly similar pattern of results to that for fluent readers, though with overall inflated response times. However, they were more distracted by pseudowords than were the fluent readers. Given that dysfluent readers were not impaired in nonword recognition, which presumably taps more orthographic than phonological processing, these findings taken together suggest a phonological locus for deficiency in dyslexic reading (cf. Moll et al., 2005). In addition, dysfluent readers showed trends for larger pseudoword and nonword deviation point effects. The larger pseudoword deviation point effect may result from a slightly slower working of the serial decoding procedure (Moll et al., 2005) or from greater distraction, caused by a pseudoword having a word-like beginning. By contrast, the larger faciltatory nonword deviation point effect can be understood in terms of a prolonged lexical search of loan-type pseudowords, such as *dattu*. The alternative explanation – that the dysfluent readers would have relatively more efficient parallel orthographic skills – would in my view be an unlikely option.

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Appendix

List of items used in Experiment 1:

Word uniqueness point:

3 or less: aisti (sense) hattu (hat) jarru (brake) johto (lead) jälki (trace) keula (fore) lampi (pond) maali (goal) pahvi (cardboard) ralli (rally) sydän (heart) vehnä (grain) aukko (hole) kampa (comb) kenkä (shoe) koulu (school) kynsi (nail) mieli (mind) miina (mine) mänty (pine) nappi (button) pukki (goat) päivä (day) sisko (sister) tieto (knowledge) tyttö (girl) vihko (notebook)
4: haamu (ghost) joulu (christmas) järki (sense) kaivo (well) lasku (bill) lause (sentence) laulu (song) lehmä (cow) linna (castle) lukko (lock) malmi (malm) masto (mast) massa (mass) mutka (turn) puuro (porridge) rauta (iron) riski (risk) risti (cross) ruusu (rose) ryhmä (group) sieni (mushroom) siipi (wing) solmu (knot) sorsa (duck) suksi (ski) taito (skill) tarve (need)
5: haave (dream) happi (oxygen) helmi (pearl) kahvi (coffee) kakku (cake) kannu (jug) kanto (stub) katto (roof) kirje (letter) kirja (book) kokko (bonfire) kukka (flower) kunto (physical condition) kuoro (choir) pallo (ball) pannu (pan) pelto (field) perhe (family) pullo (bottle) puola (rung) rasti (tick) ruutu (box) ruuti (gunpowder) suomu (scale) suomi (Finland) turve (peat) turva (safe)

Word neighbor uniqueness point:

3 or less: aisti (sense) hattu (hat) jarru (brake) johto (lead) jälki (trace) keula (fore) maali (goal) pahvi (cardboard) rally (rally) kallo (skull) kampa (comb) karja (cattle) kaula (neck) keila (bowl) kenkä (shoe) kissa (cat) koulu (school) kulta (gold) kuppi (cup) kynsi (nail) köysi (rope) laulu (song) luuta (broom) maito (milk) masto (mast) mieli (mind) miina (mine) mänty (pine) nappi (button) neula (needle) pukki (goat) puuro (porridge) ryhmä (group) sieni (mushroom) sisko (sister) solmu (knot) suksi (ski) taito (skill) tarve (need) tieto (knowledge)
4: lampi (pond) aukko (hole) haara (fork) hiiri (mouse) hiili (coal) joulu (christmas) juoru (gossip) järvi (lake) järki (sense) kaava (formula) kaivo (well) karhu (bear) kieli (tongue) kupla (bubble) kärki (tip) lasku (bill) lause (sentence) lehmä (cow) leima (stamp) linna (castle) lukko (lock) malmi (malm) massa (mass) mutka (turn) nauta (beef) paavi (pope) palmu (palm) pinta (surface) ranta (beach) rauta (iron) rauha (peace) riski (risk) risti (cross) ruoka (food) ruusu (rose) saari (iland) seula (sieve) siipi (wing) sorsa (duck) vaali (election)
5: haave (dream) haava (wound) happi (oxygen) helmi (pearl) kahvi (coffee) kakku (cake) kannu (jug) kansa (people) kanto (stub) katto (roof) kauhu (horror) kauha (scoop) kirje (letter) kirja (book) kokko (bonfire) kukka (flower) kunto (physical condition) kuoro (choir) kuuma (hot) lakko (stroke) matto (rug) pallo (ball) pannu (pan) pappi (priest) pelto (field) perhe (family) pullo (bottle) puola (pole) putki (pipe) rasti (tick) ruutu (box) ruuti (gunpowder) suola (salt) suomu

(scale) suomi (finland) takki (jacket) tappi (tenon) turve (peat) turva (safe) vaara (danger)

Pseudoword uniqueness point:

3 or less: hesmi köösi lallu lusio siupi sossa vennä vurri hottu jieto keeli könsi lusku nynsi nyttö pehvi relmi rioka sasku serhe sosko tueto tättö vuhko jelto meima mydän nattu neela nuuro **4:** kekkä kooru korru purro aikko haumu hulmi kiivo kurhu länty rieni sarhu seipi sulmu tause johno kirre laspu laupe luusa mänsy neusa nival pelmo ruopa sispo tieko haalu lyima nitel **5:** hatte helmu johte kaive kakke karhe keile kuppo kärrö köyse lehmö leime masse mutke mäntö nivem pahvo perhu päivö ryhmö siena siipo sisku solmo tietu tyttä vehnö vihku hivel ruoku

Pseudoword neighbor uniqueness point:

1: hisko holmu niipi nuoka puoru pyhmä pärry seila sohto vaamu vakku jieto nynsi nyttö relmi sasku serhe länty rieni sarhu tause haivo jelto meima mydän nattu nihko nuuro räivä **2:** juhto kekku kutto kyila körry leuse parhe pauro pilto röhmä södän hottu keeli könsi lusku pehvi rioka sosko tueto tättö vuhko aikko haumu hulmi kiivo kurhu seipi sulmu lyima mönty **3:** juiru jurru kollu kutta kynpi lemmä lutta paivi petto päävä russu sussi suumu sykän tyntö hesmi köösi lallu lusio siupi sossa vennä vurri kekkä kooru korru purro muuka neela nitel soosa **4:** kennä kärny leisa perte puuno päisä ryhnä siehi siiki solpu tytkö johno kirre laspu laupe luusa mänsy neusa nival pelmo ruopa sispo tieko haalu helsi juoku kaijo karmu keisa **5:** katte hatte helmu johte kaive kakke karhe keile kuppo kärrö köyse lehmö leime masse mutke mäntö nivem pahvo perhu päivö ryhmö siena siipo sisku solmo tietu tyttä vehnö vihku hivel ruoku

List of items used in Experiment 2:

Early uniqueness point: aalto (wave) aisti (sense) aukko (hole) hattu (hat) johto (lead) jälki (trace) keula (bow of a boat) kynsi (nail) lampi (pond) maali (goal) nahka (skin) nasta (pin) neste (liquid) niska (neck) pommi (bomb) pukki (goat) päivä (day) rally (ralli) reppu (backpack) retki (trip) enkeli (angel) erakko (loner) hiekka (sand) keikka (gig) kelkka (sledge) kihara (curl) kioski (stand) koukku (hook) liekki (flame) pimeys (darkness) pätevä (competent) pönttö (tub) ryöstö (robbery) serkku (cousin) seteli (banknote) tentti (exam) tympeä (repulsive) tyyppi (guy) ympyrä (circle) ämpäri (bucket)

Late uniqueness point: arkku (chest) haave (dream) helmi (pearl) kahvi (coffee) kakku (cake) kassa (cash) katto (roof) kauhu (horror) kilpi (plate) kirje (letter) kokko (bonfire) kunto (physical condition) kuoro (choir) lakko (strike) pallo (ball) pelto (field) pullo (bottle) putki (pipe) sänki (stubble) virka (position) haukka (hawk) haukku (bark) herkku (treat) herkkä (sensitive) korppi (crow) korppu (rusk) lantti (coin) lanttu (swede) laukka (canter) laukku (bag) palkka (salary) palkki (bar) penkka (edge) penkki (bench) pilkka (mockery) pilkku (dot) purkka (gum) purkki (can) tontti (plot of land) tonttu (elf)

Early pseudoword deviation point: jelmi rarhu sunto jakko juuta mähde vutka jiska relto rutki mauta niipi pänki vyttö mapaa juori maukku rerkkä nateus peihäs jihara sioski morppi ranttu vaukka jaukka rurkki mipaus huskea meiväs jurkea vympeä

Late pseudoword deviation point: katta keilo keulo kiela kuoru kuppo lehmo nesta pukke rallu ryhmö saaru solma sores vihke virky humino keikke kolara korkka korppo koukke lantta niukki pilkky pyykke pätevö sankku solmiu tyyppö

Early nonword deviation point: galto dattu bälki wansa zirje foski xöysi fampi dasku caavi qänty zasta qäivä wetki gieni xehnä znoppi qerkku goikka fapina felkka wiukku bätevä xaiska wäyttö xalkki dimeys curkka cyöstö gaapas deteli qäline zmpäri

Late nonword deviation point: aukkc herrw kakkf kassd kausf kuntq kynsg kärrx leimq lähtd nahkw neulz pommx pullb ruokg siskz elämyd enkelq harraz hiekkc kinkkx kämppb kääpid mokomq pilkkz putouf pönttg tenttw tonttw tonttx typerg veturf

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