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Eye movement correlates of acquired central dyslexia

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ABSTRACT

Based on recent progress in theory and measurement techniques, the analysis of eye movements has become one of the major methodological tools in experimental reading research. Our work uses this approach to advance the understanding of impaired information processing in acquired central dyslexia of stroke patients with aphasia. Up to now there has been no research attempting to analyze both word-based viewing time measures and local fixation patterns in dyslexic readers. The goal of the study was to find out whether specific eye movement parameters reflect pathologically preferred segmental reading in contrast to lexical reading.

We compared oral reading of single words of normal controls ($n = 11$) with six aphasic participants (two cases of deep, surface and residual dyslexia each). Participants were asked to read aloud lines of target words differing in length and frequency. Segmental reading was characterized by deviant spatial distribution of saccadic landing positions with initial fixations located mainly at the beginning of the word, while lexical readers showed the normative 'preferred landing positions' left to the center of the words. Contrary to expectation, word length did not distinguish between segmental and lexical readers, while word frequency showed the expected effect for lexical readers only. Their mean fixation duration was already prolonged during first pass reading reflecting their attempts of immediate access to lexical information. After first pass reading, re-reading time was significantly increased in all participants with acquired central dyslexia due to their exceedingly higher monitoring demands for oral reading.

1. Introduction

Reading disabilities due to brain disease or injury are in most cases part of a broader aphasic language disorder; they are commonly described as acquired dyslexia (Coslett, 2000; Huber, 2002a, 2002b; Papathanasiou & De Bleser, 2003). Aphasia-related reading disorders are also referred to as central dyslexia in contrast to peripheral dyslexia which is classically described as a disconnection syndrome due to an interruption between the processing of the visual input and higher level linguistic processing (Coslett, 2000; De Bleser & Luzzatti, 1989; Geschwind, 1965). Beyond the classical pure alexia, other types of peripheral – i.e. non-aphasic dyslexia were described – due to hemianopia (Leff, Scott, Crewes, Hodgson, & Cowey, 2000; Schuett, Heywood, Kentridge, & Zihl, 2008; Schuett, Kentridge, Zihl, & Heywood, 2009; Zihl, 1995a, 1995b) or attentional disorders including hemineglect (Bub, 2003).

Since the pioneering work of Marshall and Newcombe (e.g. 1966, 1973) on acquired dyslexia, different types of central reading impairment – surface, phonological and deep dyslexia – have been described in detail over the last five decades on the basis of numerous single case studies (e.g. Beaton & Davies, 2007; Behrmann & Bub, 1992; Coltheart, 1980a, 1980b, 1985; Coslett, 2000, 1991; Crisp & Lambon-Ralph, 2006; Crutch, 2006; Marshall & Newcombe, 1973; McCarthey & Warrington, 1986; Newcombe & Marshall, 1980a, 1980b, 1981; Patterson, 1988; Patterson, Marshall, & Coltheart, 1985; Rastle, Tyler, & Marslen-Wilson, 2006; Shallice & Warrington, 1980; Warrington & Shallice, 1980).

A common research methodology to distinguish the two main types of central dyslexia, surface and deep dyslexia, is linguistic error analysis of oral single word reading (Badecker & Caramazza, 1987; Dell, Schwartz, Martin, & Saffran, 1997). Oral reading in surface dyslexia is characterized by production of phonological non-words (neologisms) as a result of substitutions, omissions or additions of phonemes as well as by regularization of words with irregular orthography. Typically, persons with surface dyslexia can read pseudo-words (i.e. pronounceable non-words with regular orthography) relatively well in comparison to reading of real words. In contrast, typical features of deep dyslexia are word substitutions based on visual, lexical, semantic or morphological similarity as well as poor reading of abstract words and inability to read pseudo-words. Phonological dyslexia is often seen as a milder form of deep dyslexia without semantic word confusions.

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Error probability appears to be generally higher for segmental than for lexical errors (Coslett, 2000; Newcombe & Marshall, 1984). Therefore relatively few lexical errors may be indicative of deep or phonological dyslexia, whereas surface dyslexia is usually characterized by a high number of segmental errors. Furthermore, pure forms are extremely rare clinically, such that patients with a complete double dissociation in error distribution are hardly found within the same clinical sample (Beaton & Davies, 2007; Goldberg, 1995; Huber, 2002b).

Several computational models (see Coltheart, 2006, for a review) have attempted to account for these differences between dyslexia types. The dual route cascaded (DRC) model (Coltheart, 2006; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) postulates two distinctive reading-specific pathways that work independently from other language and cognitive systems. The non-lexical route relies on a system of grapheme-to-phoneme conversion rules which are employed in the reading of regular real words and pseudo-words in particular. The lexical route provides direct access to whole orthographic representations of words which are mapped onto phonological representations. This route is generally assumed to be utilized in the reading of highly familiar words as well as irregular words, as they do not confirm to grapheme-to-phoneme conversion rules. Only in the lexical route, semantics may mediate between access to orthographic and phonological representations. In normal reading both routes work in parallel with cooperative or competitive interaction.

Under the assumptions of the DRC model, oral reading errors in aphasia can be explained by pathological preference for one of the two reading routes, the non-lexical route in surface dyslexia and the lexical route in deep dyslexia. Preference for non-lexical route leads to segmental errors. These errors occur while the visual word form is decoded segment-by-segment from left to right, before phonological word representations may be accessed. When the process of segmentation becomes erroneous, this cannot be detected by parallel lexical access and neologistic oral reading errors may arise. In contrast, pathological preference for the lexical route may result in lexical and/or semantic reading access errors due to interference from neighboring lexical entries. The resulting word confusions remain undetected as monitoring by parallel grapheme-phoneme-conversions does not take place (Coslett, 2000; Newcombe & Marshall, 1984; Rapcsak, Henry, Teague, Carnahan, & Beeson, 2007).

From a slightly different perspective surface dyslexia can be seen as caused by a severe impairment of lexical-orthographic access or knowledge, whereas deep dyslexia is a result of an impairment of segmentation. As a consequence, the dyslexic reader attempts to circumvent the impairment by an implicitly chosen reading strategy which is error-prone. The strategy of segmental reading may lead to errors of phoneme selection as seen in surface dyslexia. The strategy of whole-word reading may lead to visual, orthographic, phonological or semantic errors in word access as characteristic for phonological and deep dyslexia. Under treatment these strategies can be enhanced and optimized (Nickels, 1995).

Although the methodology of interpreting reading errors has led to many important insights into the symptomatology and the underlying mechanisms, the method is limited to one aspect of reading aloud, the production of an articulatory response. More direct on-line evidence on information processing as provided via eye tracking may contribute to further progress by monitoring how normal and impaired word reading unfolds in real time. More specifically, it seems reasonable to assume that segmental and lexical reading strategies should be reflected in differential oculomotor behavior, but so far very little is known about the precise nature of this relationship.

Looking at experimental reading research in general, eye movement characteristics have proven highly informative with regard to the visuomotor and linguistic mechanisms mediating reading (e.g. Radach & Kennedy, 2004; Rayner, 1998). During skilled continuous reading, the eyes are moved in a sequence of very fast, relatively well coordinated, movements known as saccades. Between 80 and 95% of the saccades move progressively from left to right; the rest, referred to as regressive saccades, go back to positions that have been passed over previously. Eye movement control is word based, as evident in the so-called *preferred viewing position* phenomenon, a clustering of incoming progressive saccade landing positions in the form of Gaussian distributions with peaks between the word beginning and word center (see Radach, Inhoff, & Heller, 2003; Rayner, 1998, for discussions). As fixation positions near the word center tend to be most effective for word recognition, this is referred to as the o*ptimal viewing position* (e.g. McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; O'Regan & Jacobs, 1992).

Linguistic information is acquired during fixations, periods of relative stability with durations between 70 and over 500 ms, with means in the order of 200–250 ms. There is a clear relationship between the mental effort necessary for linguistic processing and the duration and number of fixations made. Classical notions used to describe this relation are the *eye-mind* and *immediacy assumptions* proposed by Just and Carpenter (1980). These authors suggest that processing coincides with, and is bounded by, the position fixated at any point in time, and that this processing starts at the onset of fixation and continues until all possible analyses, up to the semantic level, are completed. Subsequent research has demonstrated that the situation is slightly more complicated, as "eye" and "mind" are not always tightly synchronised. Processing can be spatially distributed so that information is acquired and processed from words that are not currently fixated, either in the form of parafoveal pre-processing or lagged verbal processing of previously fixated words (see Kliegl, Nuthmann, & Engbert, 2006, for a comprehensive discussion).

The present study focuses on two key word characteristics, word length and word frequency, which were varied in a factorial design while controlling for potential morphological and semantic influences. Word length can be seen as a major visuomotor constraint on oculomotor control and word processing, as, among other factors, the eccentricity of individual letters increases with length and more letters tend to shift saccade landing positions further into the word (Radach & McConkie, 1998). From a word processing point of view, the amount of information increases with more letters but, perhaps equally important, morphological complexity also typically increases (Bertram & Hyönä, 2003). For all these reasons word length is a powerful determinant of the probability to fixate (vs. skip) a word and of the number of fixations made. Consequently, gaze durations (the summed duration of all fixations made in first pass reading) increase substantially with longer words, which is mostly due to making more (re)fixations rather than increases in fixation durations (Blanchard, 1985).

Lexical frequency is perhaps the most extensively studied linguistic influence in experimental reading research. The frequency of a word (usually expressed in occurrences per million in normative text corpora), strongly influences how long readers look at a given, affecting both fixation and gaze duration measures (Inhoff & Rayner, 1986; Rayner & Duffy, 1986). It has been known since Just and Carpenter (1980) that word length and frequency have independent effects on gaze duration. White (2008) recently demonstrated that frequency effects are partly due to orthographic regularity, but remain strong when this influence is controlled for. Inhoff, Radach, Eiter, and Juhasz (2003) studied word length and frequency in a factorial design and found that their effects on distributed word processing and saccade planning were independent. Looking at spatial eye movement parameters, there is ample evidence that word frequency affects the likelihood of fixation and the number of fixations but apparently to a lesser extent compared to word length (Brysbaert, Drieghe, & Vitu, 2005).

Atypical eye movements in acquired dyslexia have sparked some interest in the past (e.g. Guillot, Huber, & Stiller, 1987; Huber, Lüer, & Lass, 1983; Klingelhöfer & Conrad, 1984; Lass, Huber, & Lüer, 1984), but only global oculomotor parameters were used in these initial studies. Recently, Behrmann, Shomstein, Black, and Borton (2001) for the first time reported word-based viewing times in patients with pure alexia. Pure alexia is an acquired reading disorder that arises from a low-level peripheral impairment in the graphemic recognition of letter shapes. In contrast to patients with aphasia, patients with pure alexia also called letter-by-letter readers exhibit largely intact general language skills such as writing, speaking and comprehension. Their deficit occurs early in processing at the level of extracting visual information. Letter-by-letter readers show an impaired ability to extract bottom-up information from the visual stimulus, leading e.g. to variable word length effects.

Substantially increased mean fixation durations were a major finding with letter-by-letter readers in the recent studies of Behrmann et al. (2001) and Rayner and Johnson (2005). Johnson and Rayner (2007) additionally demonstrated effects of word length and frequency and their interaction in patients with pure alexia reading sentences by means of eye movement data. They noted that the only meaningful duration measure is the total fixation time and found bottom-up effects for word length, reflected in longer total fixation times and a larger number of fixations for long words (with 5 or more characters) than for short words (with 1–4 characters). There was also a main effect for frequency. Furthermore, there was a significant interaction between word length and frequency; the frequency effect was stronger for long words than short words. These results replicate the findings of Behrmann et al. (2001), who concluded that longer words take longer to process, so that there is more time for top-down influences to affect reading times. Higher order lexical factors seem to be intact in patients with pure alexia and influence cognitive processing while reading.

So far, there has been no research in examining word length and frequency effects in a central reading disorder by means of analyzing eye movements. The goal of this study is to find distinctive temporal and spatial parameters beyond total fixation time and number of fixations in analyzing word-based viewing times and local fixation patterns to characterize central reading disorders and to distinguish between the different preferred reading strategies in subtypes of dyslexic reading.

2. Expectations and hypotheses

As discussed above, a general assumption guiding the present work is that the eye-mind hypothesis may explain in part the oculomotor behavior not only in normal but even more so in pathological reading. We expected that the eye movement pattern of dyslexic patients is largely determined by three cognitive sources of influence: (1) the overall reading strategy imposed by the type of acquired reading disorder, (2) the stimulus driven demands due to the psycholinguistic features of the individual written words to be read, and (3) the need of self-monitoring when difficulties occur in word recognition and/or reading aloud.

In the lexical type of dyslexia, the preferred *strategy* relies on whole word processing, in the segmental type of dyslexia on sequential processing of graphemes and syllables. This difference in reading strategy should be substantially reflected in spatial parameters of eye movements. We hypothesized that in lexical dyslexia landing sites of initial incoming saccades would correspond to the preferred viewing position as established for normal word reading. In contrast, initial landing sites should be shifted towards the beginning of the word in segmental dyslexia as an adaptation to the need for segmental scanning from left to right. A further distinction between the two types of dyslexia should be seen in the spatial distribution of all fixation positions across a word. In lexical dyslexia the distribution should be bell-shaped with the maximum around the center of a word, corresponding to the optimal viewing position. In segmental dyslexia the distribution should be rather flat across all letter positions, reflecting a sequential progression of relatively small refixation saccades.

Word length and lexical frequency of *stimuli* can be expected to predominantly impact temporal parameters of eye movements (see Rayner, 1998, for a comprehensive discussion of the view that word processing difficulty primarily affects viewing time measures). In normal word reading, word length strongly determines fixation probability and the number of fixations in first gaze, i.e. during the first pass reading of a word. The longer the word, the more fixations are needed. Variations in lexical frequency primarily modulate viewing durations, with less familiar words causing more mental effort as reflected in both initial fixation and gaze durations. What can be expected for the two types of dyslexia? A straightforward prediction following from our earlier discussion is that word frequency should have a particularly significant impact in lexical dyslexia, while word length may show a more pronounced effect in segmental dyslexia. Consequently, fixations should overall be longer in lexical dyslexia as opposed to more frequent fixations in segmental dyslexia.

Self-monitoring of reading difficulties may lead to regressive saccades in first gaze and/or subsequent re-reading. Thus, reading difficulties may be reflected by repeated gazes on a word and by substantially longer overall reading times. We also assumed that re-reading is more pronounced in segmental than in lexical dyslexia. This hypothesis is derived from the different probabilities of detecting errors in conditions of dyslexia. In lexical dyslexia the typical whole word confusions are less likely detected than the typical phonological errors in segmental dyslexia. Only phonological errors result in a non-word that cannot be accessed in the phonological input-lexicon during auditory self-monitoring of reading aloud. Therefore, it is noticed that "something does not compute" and a new attempt on word reading is started.

3. Methods

3.1. Participants

The study included a sample of 17 participants consisting of controls ($n = 11$) and patients ($n = 6$). The control group comprised eleven native speakers of German, five males and six females aged between 16 and 61 years (mean 37 years). All showed normal or corrected to normal vision and no history of neurological or psychiatric disabilities. Their mean years of school education were 11.8 (range 8–13 years).

The six patients were recruited from the aphasia ward of the RWTH Aachen university hospital, where they received an intensive 7-week treatment (Huber, Springer, & Willmes: Aachen approaches, 1993). Patients were selected when they reached at least a percentile rank of 50 in reading aloud single words and short sentences as assessed by the subtest on Written Language of the Aachen Aphasia Test (AAT; Huber, Poeck, Weniger, & Willmes, 1983; Huber, Poeck, & Willmes, 1985). Five patients were premorbidly right-handed; one was ambidextrous as assessed by the Edinburgh Inventory (Oldfield, 1971). All were native monolingual speakers of German and demonstrated vision and hearing acuity in the normal range. Type and degree of aphasia was derived from the complete performance profile of the AAT. The main characteristics of the six patients are given in Table 1. The patients are grouped according to their reading performance and/or their oculomotor behavior.

The etiology was vascular in all patients. Five suffered from an infarct and one from a hemorrhage in the MCA territory. The lesions of all patients are shown in Fig. 1. In two patients (WH, CB), the frontal eye field (FEF) was clearly not damaged, while in two other patients (MB, KB), the lesion affected the frontal white matter in the vicinity of the FEF. In the remaining two patients (CG, IT) the lesion extended into central white matter.

Patient WH is a 61-year-old male technical designer who sustained a small infarct in the left middle MCA territory with damage to the precentral gyrus. Patient CG is a 51-year-old female high school principle who sustained an infarct in the left middle MCA territory affecting basal ganglia, posterior insular cortex, auditory

Table 1
Main characteristics of aphasic patients.

Patient	Lexical readers			Segmental readers		
	WH	CG	CB	MB	KB	IT
Gender	Male	Female	Female	Male	Male	Female
Age in years	61	51	46	35	56	57
Etiology	Infarct	Infarct	Infarct	Infarct	Infarct	Hemorrhage
Hemisphere	Left	Left	Right	Left	Left	Left
Duration post-onset in months	13	20	9	4	18	53
AAT						
Overall severity[a]	Mild	Mild	Residual	Residual	Moderate	Mild
Severity in written language[b]	Mild	Mild	Residual	Mild	Moderate	Mild
Aphasia syndrome classification[c]	Anomic	Broca's	Residual	Broca's	Broca's	Wernicke's

[a] Derived from mean profile height of all AAT subtests (at time of examination).
[b] Derived from percentiles of AAT subtest written language.
[c] Allocation to aphasic syndrome by means of a non-parametric discrimination analysis program (Huber et al., 1983; Habbema, Hermans, & van den Broek, 1974).

cortex and supramarginal gyrus extending into central white matter. Patient CB is a 46-year-old female bank employee who sustained an extended right hemisphere infarct in the MCA territory after clipping an MCA aneurysm. The patient is ambidextrous. CAT-scan revealed damage to Broca's area, insular cortex, central operculum, supramarginal gyrus and superior temporal gyrus including Wernickes's area. Patient MB is a 35-year-old male newspaper journalist suffering from an infarct of the left anterior and central MCA-territory with damage to Broca's area, central operculum, anterior insular cortex, central and frontal white matter. Patient KB is a 56-year-old male policeman who sustained an extended left MCA infarct. The damage included perisylvian cortical and sub-cortical areas of the frontal, temporal and parietal lobe (save for the supramarginal gyrus). The central and white matter was also affected. Furthermore, the visual tract appears to be compromised by the lesion. However, no visual field defect was present on perimetric testing (Goldmann) 4 months post-onset. Patient IT is a 57-year-old female college lecturer who sustained a left basal ganglia hemorrhage. The resulting damage also included Broca's area, central operculum, central and white matter.

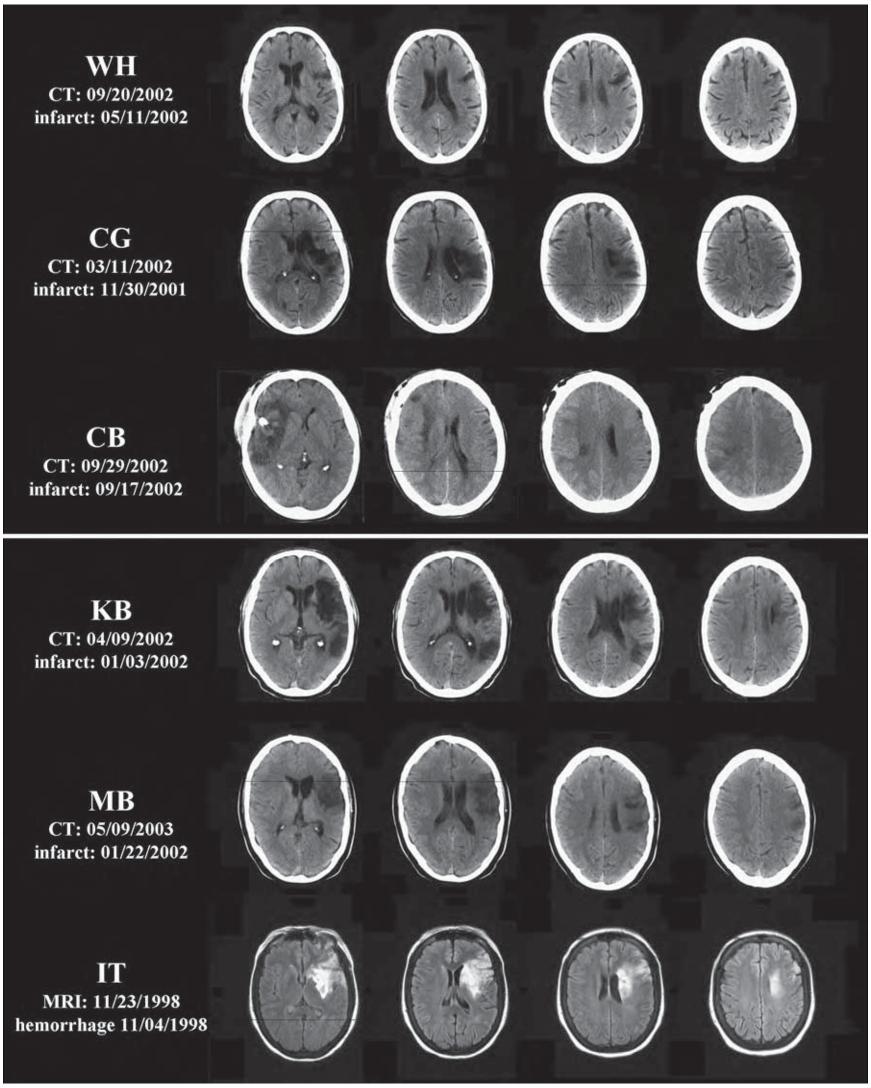

Fig. 1. Lesion of the six patients; time post-onset varies between 8 days and 15 months post-onset.

Table 2
Results of the linguistic reading error analysis – six patients and their classification of dyslexia due to their distribution of reading errors.

Patient (aphasia)	WH (anomic)	CG (Broca's)	CB (residual)	MB (Broca's)	KB (Broca's)	FT (Wernicke's)
Correct responses (of $n = 64$)	47	24	60	44	40	53
Lexical errors						
Absolute number	7	15	0	4	3	5
Confidence interval	(5–21)	(18–36)	–	(2–15)	(1–13)	–
Proportion in percent	41%	40.5%	–	20%	12.5%	–
Segmental errors						
Absolute number	10	22	4	16	21	6
Commence interval	(8–27)	(23–47)	–	(15–37)	(22–46)	–
Proportion in percent	59%	59.5%	–	80%	87.5%	–
Difference between error types*	$p = 0.629$	$p = 0.324$	–	$p = 0.012$	$p = 0.001$	–
Characteristic reading error	Lexical	Lexical	Residual	Segmental	Segmental	Residual

* Exact test with $p = 0.5$ of binomial distribution, two-sided.

3.2. Materials of the experimental reading task

A set of 64 German stimulus words was developed, varying two key psycholinguistic parameters, word familiarity (e.g. Bertram & Hyönä, 2003; Gernsbacher, 1984; Monsell, 1991; Rayner, 1998; White, 2008) and word length (e.g. Juhasz & Rayner, 2003; O'Regan, 1990; O'Regan & Jacobs, 1992; Vitu, O'Regan, & Mittau, 1990; Ziegler, Perry, Jacobs, & Braun, 2001), which are commonly used in research on word processing in continuous reading. Word length was categorically determined as medium (7–8 letters) and long (11–12 letters). Shorter words were not considered, as stimuli were intended to elicit at least one fixation per word in normal readers and more than one fixation in patients. The two sets of 32 medium and long words were balanced in terms of morphological properties so that half of the stimuli were compounds, the other half were simplex or derivative words.

Word familiarity rather than word frequency was used as the primary parameter of lexical difficulty,[1] since some of the stimulus words we were interested in had no entry in the German CELEX data base and a rating study was necessary anyway to control for concreteness/imageability.[2]

A total of 365 potential target words was selected for the rating task with variation in length (medium vs. long) and morphological structure (simplex, derivative, compound). All potential target words were given in fixed randomized order to a group of 20 participants who did not participate in the main reading experiment. They were asked to rate these target words on a 7-point scale of familiarity from 1 (very high) to 7 (very low) and of imageability from 1 (very concrete/easily depictable) to 7 (very abstract/not depictable). Words rated 4 ("medium") were excluded from the stimulus selection. Based on the results of the rating study, the final item set was composed of four subsets of 16 items each. Four linguistic variables – word length, morphological structure, lexical familiarity and concreteness – were exactly matched across cells. High and low familiarity items were compared to the German CELEX frequency counts of written words, which are based on a corpus of 5.4 million word tokens (Baayen, Piepenbrock, & Gulikers, 1995). Mean written frequency for high familiarity items was 54.03 (SD 111.83, range 0.00–903.89), in contrast to 0.62 (SD 0.14, range 0.00–0.93) for low familiarity items. As could be expected, this difference was highly significant (exact $p < 0.001$, Mann–Whitney *U*-test). The difference is also well within the range of word frequency contrasts typically used in research on normal readers both in English (e.g. Inhoff & Rayner, 1986; Rayner & Duffy, 1986) and German (e.g. Radach, Huestegge, & Reilly, 2008).

During the reading experiment participants were asked to read aloud words that were arranged in lines as in normal sentence reading. This task preserves the normal sequence of eye movements along a line while avoiding higher order processing demands of continuous text reading that would have overwhelmed most of our patients.

The total task consisted of eight lines which were individually presented on a computer screen. Positions with lines were counterbalanced with respect to the linguistic parameters manipulated in this study.

3.3. Reading behavior and error analysis

The articulations of all participants were digitally recorded on a computer (WaveLab – Steinberg Media Technologies; www.steinberg.net) for subsequent linguistic analysis. Most control participants performed the task without any errors (minimum 61 out of 64 correct oral word productions). The few reading errors consisted mostly of either hesitations or self-corrections. In contrast, four of the patients did not reach a mastery criterion of 90% (≥53 correct, $N = 64$ binomial distribution; see Table 2). The two other patients showed only residual symptoms of dyslexia and reached mastery performance (53 correct in IT, 60 correct in CB).

An error analysis was performed in the four clearly dyslexic patients to identify segmental and lexical reading difficulties. Lexical difficulties are characterized by whole word substitutions being either semantically, phonologically or visually related to the target. Segmental difficulties are indicated by phonological neologisms, i.e. the spoken respond does not belong to the German lexicon as a result of single or multiple phoneme encoding errors.

MB and KB had significantly more segmental errors than lexical errors, while WH and CG also made a substantial amount of lexical errors (more than 40%; see Table 2). As suggested in the introduction, these error patterns can be related to different underlying reading strategies. In lexical reading, immediate access to lexical knowledge is attempted, whereas in sublexical reading the visual word form is decoded segment-by-segment. These differences in reading strategies should be reflected in differential oculomotor behavior.

3.4. Apparatus and procedure for eye movement data collection

Eye movements and head position were recorded using an SR EyeLink II video-based head-mounted eye tracking system. The registration is based on infrared-light reflection from pupil and cornea at a sampling rate of 250 Hz. Viewing was binocular but eye movements were recorded from the right eye only. Head position was recorded by an additional head-mounted camera and small movements were compensated on-line. After fitting the headband, the participant's eye position was calibrated using 3 black dots placed equidistantly on a horizontal target line. Targets were presented individually in fixed order and subjects were asked to fixate each dot, which was automatically controlled by the eye tracking system. Calibration was initiated and carried through by the participant pressing the space bar on the keyboard. Calibration was immediately followed by a validation routine that determined the stability and accuracy of the initial measurement.

The target words were displayed in black on a grey background using a 21-in. CRT monitor running at a resolution of 1024 × 768. Text was displayed in non-proportional 15 point Courier font corresponding to 12 pixels horizontally. At a viewing distance of 54 cm, each character subtended approximately 0.5° of visual angle. Blanks before words had the width of a character. After calibration the reading task was introduced using one line of eight practice items. Participants were asked to fixate a cross at the left end of the line before the eight written words were shown simultaneously. This was the signal to start reading aloud all eight words in a sequence. When finished, the participant pressed the space bar which caused the stimuli to disappear and to present a new fixation cross.

3.5. Data selection and analysis

A target word was included in the data analysis when a fixation fell on at least one of its constituent letters or on the blank space preceding it. Data were organized in terms of pairs of incoming saccades and following fixation durations. Excluded from analysis were observations containing blinks or fixation durations shorter than 70 ms or longer than 2500 ms and/or three standard deviations of the mean. Cases were also excluded when saccade amplitudes were shorter than one letter or longer than 20 letters. In combination, these criteria led to the exclusion of 9.6% of the total data. To ensure that all observations were part of a dynamic routine of reading, the first fixation position and duration on each line were not considered in the computation of distributions and cell means.

As a first step of the analysis, the so-called main sequence (i.e. the relationship between saccadic amplitude and peak velocity) was computed from the final data set as a control measure for basic visuomotor functioning on a sub-cortical level. The relationship between saccadic amplitude and peak velocity is commonly found to be linear in healthy participants, indicating normal operation of the brainstem circuitry underlying oculomotor control (Bahill, Clark, & Stark, 1975; Carpenter, 1988).

[1] Rayner et al. (2004) demonstrated that frequency, familiarity and age of acquisition have a very similar influence on eye movement parameters as gaze duration in reading.

[2] Gilhooly and Hay (1977) as well as Paivio et al. (1968) showed that imageability and concreteness are highly correlated.

Table 3
Definitions of spatial parameters used for eye movement measurement.

Spatial parameters	Definition
Landing position of initial progressive saccades	Position (in letters) where the first fixation of a progressive (i.e. in reading direction) saccade within the target word is located (letters are numbered according to their serial position counting from left-to-right; the empty space before a word is coded as 0)
Landing position of all saccades in the first gaze	Position (in letters) where the mean of all fixations (of progressive and regressive saccades) within the first reading pass (first gaze) is located
Landing position of all saccades in all gazes	Position (in letters) where the mean of all fixations (of progressive and regressive saccades) within the all reading passes (all gazes) is located
Amplitude of initial progressive saccade	Length, in letter positions, of the first incoming progressive saccade into the target word
Amplitude of all saccades in the first gaze	Mean length, in letter positions, of all progressive and regressive saccades on the target word in the first reading pass (first gaze), i.e. including the initial saccades amplitude and following intra-word saccade amplitudes
Amplitude of all saccades in all gazes	Mean length, in letter positions, of all progressive and regressive saccades of the target word in all reading passes (all gazes), i.e. including all intra-word and all inter-word saccade amplitudes

Table 4
Definitions of temporal parameters used for eye movement measurement.

Temporal parameters	Definition
First fixation duration in the first gaze	Duration in ms of the initial fixation within a target word
Mean fixation duration in the first gaze	Mean in ms of all fixation durations of the target word within first pass reading (first gaze) including the first fixation duration and the following fixation durations
Refixation time in the first gaze	Summed duration time in ms of all refixations within the first reading pass (first gaze) excluding the first fixation duration, but including the following refixation durations
First gaze duration	Summed duration in ms of all fixations in first pass reading (first gaze) before leaving the word (but excluding the duration of saccadic eye movement)
Total number of fixations in the first gaze	Total number of all fixations within first pass reading (first gaze)
Total reading time in all gazes	Summed duration time in ms of all fixation within the target word including the fixation durations within re-reading the target word after leaving
Re-reading time in all gazes	Summed duration time in ms of all re-reading fixation times excluding the fixation time of the gaze duration in first pass reading including summed fixation times of second and more pass reading (second, third, etc. gazes)
Total number of fixations in all gazes	Total number of all fixations within all reading passes (all gazes)
Total number of all gazes	Total number of reading passes or gazes per target word

Reading-related analysis of eye movements commonly makes use of spatial and temporal parameters as defined in Tables 3 and 4 (e.g. Inhoff & Radach, 1998; Radach & Kennedy, 2004). Analyses of spatial parameters focus on saccade landing positions and amplitude. To study effects of independent linguistic stimulus variables, the following parameters were considered: first fixation duration, refixation, re-reading and total reading time as well as mean fixation duration and frequency of fixations in first gaze. Descriptive and inferential statistical analyses were computed using SPSS. Individual temporal and spatial eye movement parameters of the six individual patients were contrasted to those of the controls.

With respect to the controls ($n = 11$), the effects of independent variables on key oculomotor measures were examined using standard repeated measures analysis of variance (ANOVA).

A modified t-test suggested by Crawford and Howell (1998) served to analyze individual patient data via comparison with control group means. To assess the impact of linguistic parameters on the eye movement behavior of individual patients, the non-parametric Mann–Whitney U-test was used. According to expectation, all estimates of p values are one-sided.

4. Results

4.1. Saccade velocities

We first examined the saccadic main sequence, i.e. the relationship between the amplitude of all progressive saccades and their peak velocity in degrees per second. On average, we obtained 172 observations of saccades for the control group (mean within subject peak velocity $131^\circ\,s^{-1}$, SD $64^\circ\,s^{-1}$, range $15–355^\circ\,s^{-1}$). In the six patients we obtained between 215 and 294 saccades (mean peak velocity $82–170^\circ\,s^{-1}$, SD $37–88^\circ\,s^{-1}$, range $17–423^\circ\,s^{-1}$). The main sequence is plotted in Fig. 2 for saccades ranging in lengths between 0.5° and 4° amplitudes (equivalent to 1 and 8 letters). All

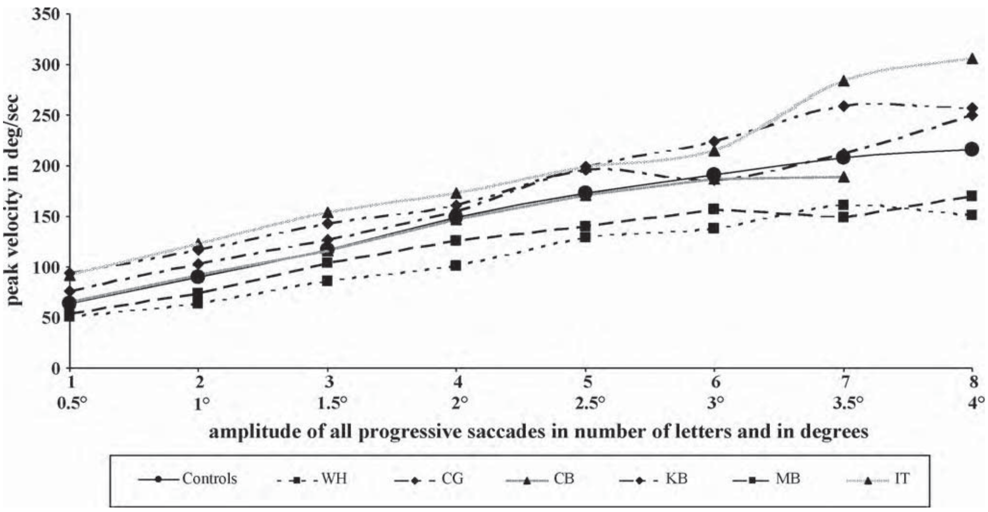

Fig. 2. Main sequence as a function of the amplitude of all progressive saccades and their peak velocity in degrees per second.

Table 5
Spatial parameters of saccades: landing positions and amplitudes (mean and standard deviation (SD) measured in letter units).

$n=64$ 7–8 letters ($n=32$) 11–12 letters ($n=32$)		Controls ($n=11$)		Lexical readers						Segmental readers					
				Patient WH		Patient CG		Patient CB		Patient MB		Patient KB		Patient LT	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Landing position of initial progressive saccades in the first gaze	7–8 letters	2.63	1.40	2.96	1.99	2.80	1.83	2.26	1.61	2.05	1.68	1.75	2.17	1.83	1.83
	p-Value[*]			0.321		0.455		0.403		0.350		0.280		0.298	
	11–12 letters	3.17	1.51	3.45	1.77	3.13	2.03	3.21	1.55	2.39	2.75	3.04	2.80	2.19	2.32
	p-Value[*]			0.431		0.490		0.490		0.316		0.468		0.274	
Landing position of all saccades in the first gaze	7–8 letters	3.71	1.84	3.07	1.98	4.27	1.99	3.99	1.92	3.25	2.41	3.71	2.67	3.05	2.24
	p-Value[*]			0.373		0.388		0.444		0.408		0.500		0.369	
	11–12 letters	5.46	2.71	4.82	2.79	6.10	2.83	6.25	3.16	4.37	3.44	6.81	3.32	3.91	3.10
	p-Value[*]			0.413		0.413		0.393		0.354		0.322		0.298	
Landing position of all saccades in all gazes	7–8 letters	3.76	1.87	3.41	3.00	4.32	4.00	4.04	4.00	3.51	3.00	3.94	4.00	3.63	4.00
	p-Value[*]			0.431		0.390		0.444		0.450		0.464		0.474	
	11–12 letters	5.50	2.72	5.10	5.00	6.38	6.00	6.34	6.00	5.91	6.00	6.99	7.00	5.61	6.00
	p-Value[*]			0.445		0.382		0.387		0.444		0.306		0.485	
Amplitude of initial progressive saccades in the first gaze	7–8 letters	6.77	2.24	6.31	1.87	5.41	2.11	4.55	1.51	6.66	3.24	5.08	3.48	6.84	3.71
	p-Value[*]			0.424		0.287		0.183		0.482		0.243		0.488	
	11–12 letters	6.93	2.29	6.52	1.46	5.42	2.22	5.25	1.71	7.25	3.52	5.62	3.07	7.15	4.13
	p-Value[*]			0.434		0.271		0.249		0.448		0.298		0.464	
Amplitude of all saccades in the first gaze	7–8 letters	2.95	4.10	1.21	3.99	2.00	3.54	1.35	2.68	1.29	5.03	2.98	3.53	2.84	4.55
	p-Value[*]			0.347		0.414		0.358		0.353		0.497		0.490	
	11–12 letters	2.82	3.80	1.12	3.67	1.82	3.50	1.00	4.82	1.80	5.24	2.15	3.74	2.16	5.13
	p-Value[*]			0.339		0.403		0.328		0.401		0.435		0.436	
Amplitude of all saccades in all gaze	7–8 letters	2.54	4.85	1.01	1.83	1.61	2.21	1.07	1.98	0.72	1.39	2.07	2.47	1.28	1.51
	p-Value[*]			0.384		0.429		0.389		0.363		0.464		0.404	
	11–12 letters	2.55	4.30	1.14	2.05	1.77	2.46	1.47	2.42	0.77	1.16	1.51	2.15	1.23	2.10
	p-Value[*]			0.380		0.433		0.407		0.350		0.411		0.387	

[*] p-Values refer to differences between control group and each individual patient (t-test (Crawford & Howell, 1998); $\alpha = 0.05$, one-sided).

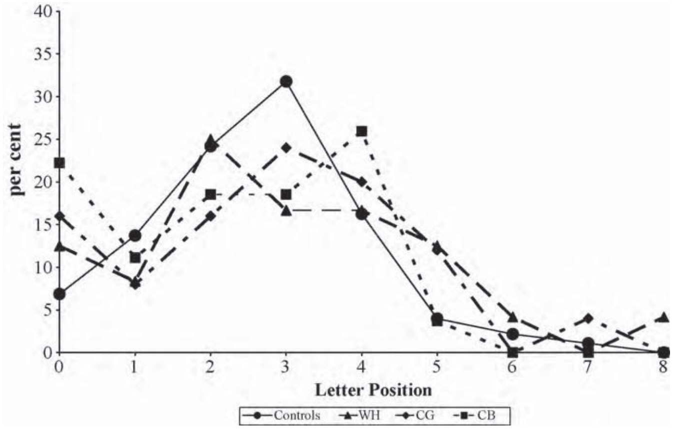

Fig. 3. Landing positions of *initial* progressive saccades into 7–8 letter target words for controls and three patients WH, CG (lexical readers) and CB (residual dyslexia).

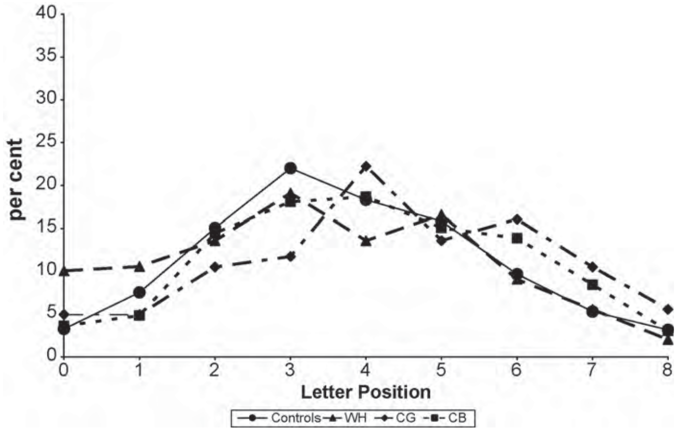

Fig. 5. Landing positions for *all* saccades in all gazes into 7–8 letter target words for the controls and three patients WH, CG (lexical readers) and CB (residual dyslexia).

six patients showed a normal acceleration with increasing lengths of saccades. Thus, we can conclude that the basic brainstem circuitry supporting the oculomotor system was undisturbed in all patients (see Ciuffreda & Tannen, 1995, for a discussion of the main sequence in clinical research).

4.2. Spatial saccade parameters

Distance values for landing positions and amplitudes of saccades are given in Table 5. Distance is measured in units of individual letter width which was 0.5° of visual angle for each letter type. Pairwise comparison (modified *t*-test) between individual patients and the control group yielded no significant difference for any of the parameters. Contrary to expectation, this was also true for the segmental readers who did not show shorter mean amplitudes of saccades.

As a next step we calculated the landing site distribution of saccades in terms of individual letter positions. In Figs. 3 and 4 the results for initial progressive saccades into target words of 7–8 letters are shown. The control group has a peak on letter 3, which is slightly left to the middle of the target word, corresponding to the "preferred viewing position" found previously in skilled sentence reading (Rayner, 1979). The three patients depicted in Fig. 3 (WH, CG and CB) showed distributions of similar shape with peaks between letter positions 2 and 4. These peak locations are well within the individual variation usually seen in skilled readers, indicating that, despite somewhat larger variability, their initial landing positions were quite normal. This results clearly points to a lexical reading strategy, i.e. the attempt to perceive and recognize the word as a whole on first fixation. In two of these patients (WH and CG), lexical reading is also demonstrated by their error pattern (see Table 2).

A strikingly different pattern was found for the three other patients (MB, KB and IT). Their frequency peaks are shifted to the extreme left, as their initial progressive saccades mostly landed at the very beginning of the word or even at the space before (see Fig. 4). This pattern is likely to reflect a segmental strategy of reading. Again, in two of the patients (MB and KB), this view is supported by their error pattern in reading aloud (cf. Table 2). In the third patient (IT) error rates were too low to allow supporting any hypothesis on the underlying reading strategy. However, the eye movement pattern of IT quite clearly indicates a preference for segmental reading, suggesting a high sensitivity of oculomotor data even in the absence of articulation errors. Very similar results were obtained for long target words of 11–12 letters.

A clear difference between lexical and segmental aphasic readers was also found when the distribution of landing positions of all saccades during all gazes was calculated. In Figs. 5 and 6 this is again illustrated for target words of 7–8 letters length. The lexical readers tend to show normal bell-shaped distribution patterns (see Fig. 5), indicating that, over all observations, saccades tend to converge towards positions that are generally optimal for word recognition (O'Regan & Jacobs, 1992). This is sharp contrast to a nearly flat dis-

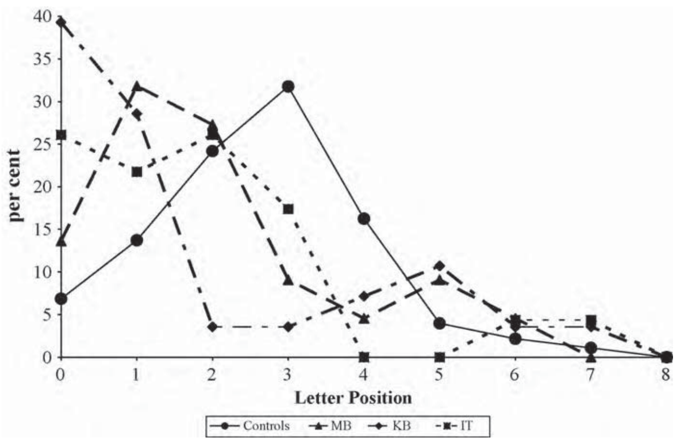

Fig. 4. Landing positions for *initial* progressive saccades into 7–8 letter target words for the controls and three patients MB, KB (segmental readers) and IT (residual dyslexia).

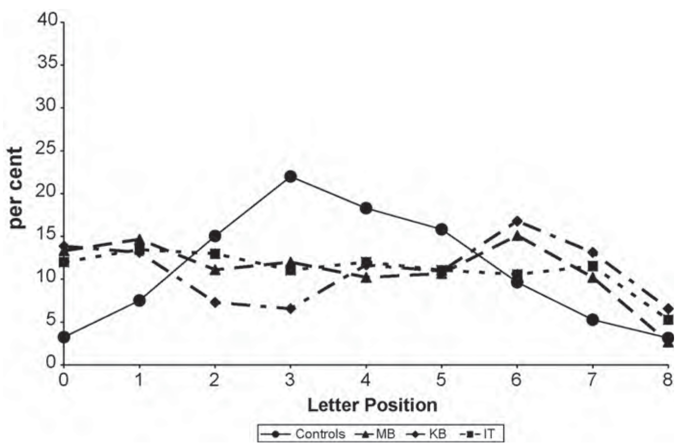

Fig. 6. Landing positions for *all* saccades in all gazes into 7–8 letter target words for the controls and three patients MB, KB (segmental readers) and IT (residual dyslexia).

Table 6
Temporal parameters of fixation and gaze (mean and standard deviation (SD) for duration in ms and for total number).

$n = 64$ 7–8 letters ($n = 32$) 11–12 letters ($n = 32$)		Controls ($n = 11$)		Lexical readers						Segmental readers					
		Mean	SD	Patient WH		Patient CG		Patient CB		Patient MB		Patient KB		Patient LT	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
First fixation duration (ms) in the first gaze	7–8 letters	401	53	340	129	423	234	246	120	288	174	367	193	277	148
	p-Value*			0.148		0.350		0.009		0.034		0.276		0.025	
	11–12 letters	356	52	358	217	404	222	322	119	310	201	380	274	340	196
	p-Value*			0.486		0.199		0.273		0.208		0.334		0.387	
Mean fixation duration (ms) in the first gaze	7–8 letters	352	66	368	102	421	170	304	67	282	127	416	172	284	107.00
	p-Value*			0.411		0.170		0.251		0.167		0.188		0.174	
	11–12 letters	310	56	358	77	410	173	298	86	281	174	340	199	296	170
	p-Value*			0.215		0.059		0.421		0.315		0.310		0.408	
Refixation time (ms) in the first gaze	7–8 letters	452	180	1274	1040	946	687	1345	690	826	1175	837	955	280	442
	p-Value*			0.001		0.013		<0.001		0.037		0.034		0.191	
	11–12 letters	714	200	2348	1534	1526	1517	991	860	383	771	1244	1246	686	952
	p-Value*			<0.001		0.002		0.107		0.072		0.015		0.448	
Gaze duration (ms) in the first gaze	7–8 letters	850	192	1604	1005	1379	731	1594	643	1091	1147	1203	991	615	538
	p-Value*			0.002		0.012		0.002		0.129		0.054		0.134	
	11–12 letters	1070	230	2631	1545	1933	1568	1313	835	693	767	1625	1271	1026	1050
	p-Value*			<0.001		0.002		0.168		0.074		0.022		0.429	
Total number of fixations in the first gaze	7–8 letters	2.63	0.64	4.30	2.54	3.32	1.64	5.32	1.97	8.93	5.18	2.72	2.11	2.14	1.69
	p-Value*			0.016		0.163		0.001		<0.001		0.448		0.240	
	11–12 letters	3.68	0.74	7.07	4.09	4.61	3.64	4.59	2.70	2.62	3.02	4.17	3.12	3.57	3.11
	p-Value*			0.001		0.128		0.133		0.100		0.270		0.445	
Total reading time (ms)	7–8 letters	965	168	2662	1036	2328	1296	1715	613	2584	1631	2213	1000	2111	1439
	p-Value*			<0.001		<0.001		0.001		<0.001		<0.001		<0.001	
	11–12 letters	1219	178	3543	1334	3038	1225	1860	593	3286	1574	2741	1679	4243	2803
	p-Value*			<0.001		<0.001		0.003		<0.001		<0.001		<0.001	
Re-reading time (ms)	7–8 letters	115	91	1095	1432	949	1626	120	306	1493	1615	1010	1349	2131	1476
	p-Value*			<0.001		<0.001		0.480		<0.001		<0.001		<0.001	
	11–12 letters	149	131	710	1202	1105	1288	546	815	2593	1984	1117	1362	3216	2578
	p-Value*			0.001		<0.001		0.008		<0.001		<0.001		<0.001	
Total number of fixations	7–8 letters	3.08	0.68	7.13	2.78	5.81	3.20	5.71	1.81	8.93	5.18	5.53	3.05	9.86	4.69
	p-Value*			<0.001		0.002		0.002		<0.001		0.003		<0.001	
	11–12 letters	4.24	0.82	9.50	3.13	7.84	2.90	6.50	1.50	11.73	5.01	7.23	5.50	15.73	8.65
	p-Value*			<0.001		0.001		0.012		<0.001		0.003		<0.001	
Total number of all gazes	7–8 letters	1.26	0.19	2.17	1.39	1.90	1.14	1.26	0.51	3.00	1.58	2.28	1.53	4.68	2.58
	p-Value*			0.001		0.005		0.500		<0.001		<0.001		<0.001	
	11–12 letters	1.26	1.75	1.77	0.86	2.00	1.15	1.41	0.62	3.50	1.82	2.10	1.30	5.23	2.05
	p-Value*			0.393		0.347		0.468		0.124		0.328		0.027	

* p-Values refer to differences between control group and each individual patient (t-test (Crawford & Howell, 1998); $\alpha = 0.05$, one-sided).

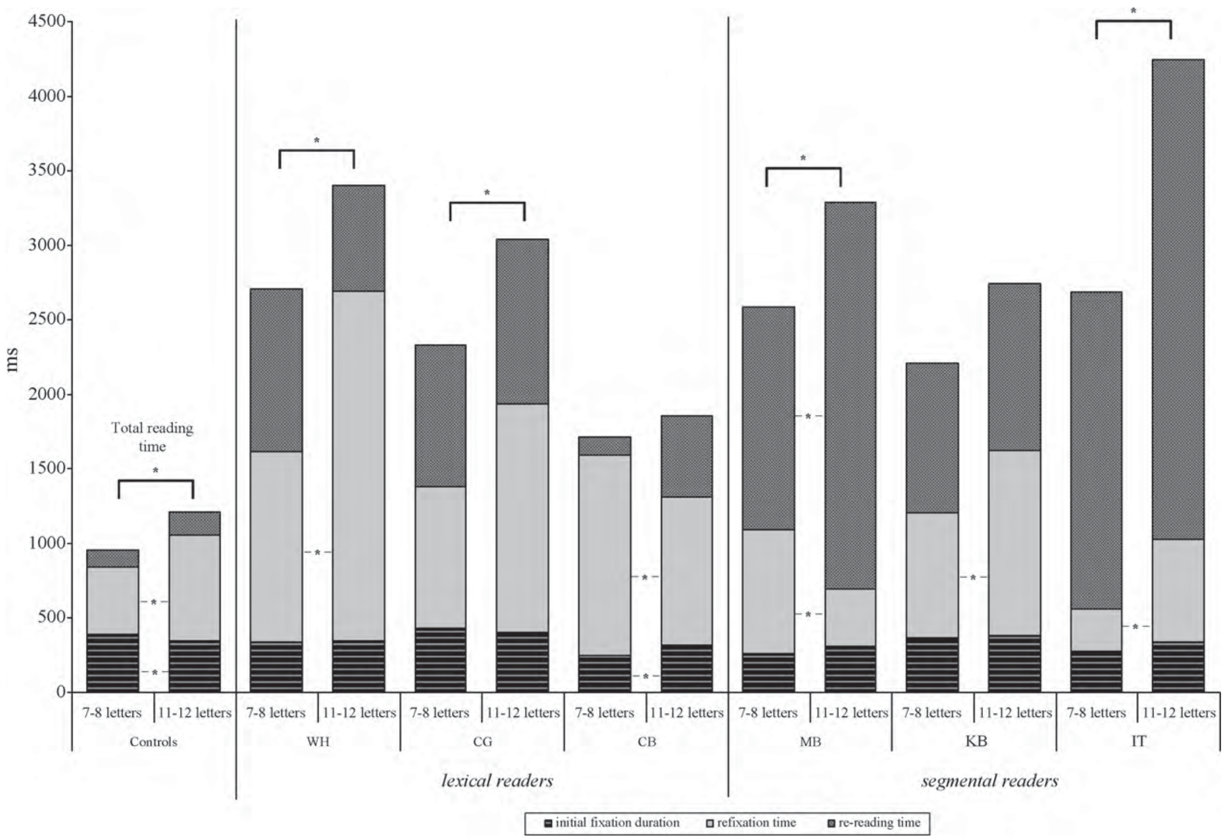

Fig. 7. Stacked Bars of initial fixation duration and refixation time during the first gaze and re-reading time during the following gazes per word length for the controls and the six patients (*indicates significant difference between word length, $\alpha = 5\%$; one factorial repeated analysis of variance (ANOVA) for controls, non-parametric Mann–Whitney *U*-test for monotone trend for estimation of exact *p*-value for individual patient).

tribution found for segmental reading of MB, KB and IT (see Fig. 6), again suggesting primarily sequential reading. This difference was less pronounced for long target words, possibly because lexical readers were less able than controls to treat longer words as a holistic lexical entity, leading to more spatially distributed within-word saccades and hence a leveling of their landing site distributions.

4.3. Temporal parameters

The results for duration and frequency of fixation and gaze are given in Table 6. The parameters for first gaze (upper part of Table 6) show no consistent differences between patients and controls, whereas the parameters for all gazes together (lower part of Table 6) were found to have longer or higher values for nearly each patient. Total reading time was significantly longer in all six patients (1715–2777 ms for middle and 1860–4243 ms for long words in contrast to a mean of 965 ms for medium and 1219 ms for long words in the controls). Interestingly, the same pattern was found when of re-reading time was considered in isolation (with the exception of patient CB on medium length target words).

In all patients the increase in reading time was due to significantly higher total numbers of all fixations for both shorter and longer words. Even the total number of gazes was always significantly higher than in controls for words of medium length (except for CB), but for long words the difference was not significant due to higher variability in normal controls.

Contrary to expectation, the difference between lexical and segmental readers was not reflected in temporal parameters obtained in the first gaze (upper part of Table 6). Apparently, in many cases first pass reading was generally not sufficient for complete recognition of a target word so that a large proportion of extra processing was accumulated during later passes. It should be noted, however, that on each first gaze parameter, except for mean fixation duration, there were always between 3 and 5 patients who showed values significantly different from the controls, irrespectively of their preferred lexical or segmental reading strategy. The relatively weak discriminatory power of mean fixation duration illustrates the fact that the more specific word-based measures should perhaps be given preference in comparative oculomotor analyses of this type (Inhoff & Radach, 1998).

4.4. Linguistic parameters

We also examined how the eye movement patterns were influenced by word length and lexical familiarity. Fig. 7 shows the means of initial fixation duration, refixation time and re-reading time in ms for 7–8 letter and 11–12 letter words per patient and for the control group. As expected, controls showed significantly longer refixation times and total reading times for long words (11–12 letters) in contrast to medium words (7–8 words). Four of the patients (two with lexical and two with segmental dyslexia each) also showed significant word length effects on total reading time.

Closer inspection of the data revealed that in normal controls the variation in word length resulted in a trade-off between fixation frequency and mean fixation duration. More but shorter fixations were obtained for long words. Quite strikingly, no such trade-off effect was found for the six dyslexic readers (see Table 7). Mean fixation duration in the first gaze did not differ between medium and long words, total number of fixations were increased as expected in two segmental readers (KB and IT) and contrary to expectations in one lexical reader (WH).

Table 7
Word length effect/trade-off effect (mean and standard deviation (SD) for duration in ms and for total number).

$n = 64$ 7–8 letters ($n = 32$) 11–12 letters ($n = 32$)		Controls ($n = 11$)		Lexical readers						Segmental readers					
		Mean	SD	Patient WH		Patient CG		Patient CB		Patient MB		Patient KB		Patient IT	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean fixation duration (ms) in the first gaze	7–8 letters	352	66	368	102	421	170	304	67	282	127	416	172	284	107.00
	11–12 letters	310	56	358	77	410	173	298	86	281	174	340	199	296	170
	p-Value*	0.008		0.404		0.461		0.303		0.364		0.280		0.413	
Total number of fixations in the first gaze	7–8 letters	2.63	0.64	4.30	2.54	3.32	1.64	5.32	1.97	8.93	5.18	2.72	2.11	2.14	1.69
	11–12 letters	3.68	0.74	7.07	4.09	4.61	3.64	4.59	2.70	2.62	3.02	4.17	3.12	3.57	3.11
	p-Value*	<0.001		0.002		0.155		0.225		0.050		0.010		0.032	

* Values of patients refer to (non-parametric) Mann–Whitney U-test for monotone trend for estimation of exact p-value
p-Values of controls refer to one factorial repeated measure of analysis of variance (ANOVA).

Surprisingly, the third segmental reader (MB) showed for long words even a decrease in number of fixations at the cost of significantly extended re-reading time. It is tempting to conclude that MB gave up early on first pass reading of long words and instead re-inspected these words frequently, spending almost twice as long as in first gaze.

The impact of word familiarity on the components of total reading time is illustrated in Fig. 8, indicating that highly familiar were always recognized significantly faster than low familiar words. This effect was obtained for total reading time in all participants, except for the segmental reader KB. Interestingly, the distinction between lexical and segmental readers emerged when first gaze duration (sum of initial fixation duration and refixation time) was compared between low and high familiar words. The expected familiarity effect was only found for the lexical readers (CB: $p < 0.001$, WH: $p = 0.005$, CG: $p = 0.003$ in contrast to IT: $p = 0.181$, MB: $p = 0.203$, KB: $p = 0.359$; Mann–Whitney U-test, one-tailed).

In Table 8, the impact of word familiarity on duration and number of fixations in the first gaze (first pass reading) is shown. The control group exhibits a significant effect on number of fixations, which is also found in all lexical readers but in none of the segmental readers. In addition, the lexical readers also exhibit a significant or nearly significant effect of familiarity on the mean fixation duration in the first gaze.

5. Discussion

In the present study, we examined six aphasic patients with acquired central reading disorders after stroke. We analyzed their performances of oral single word reading to classify them into

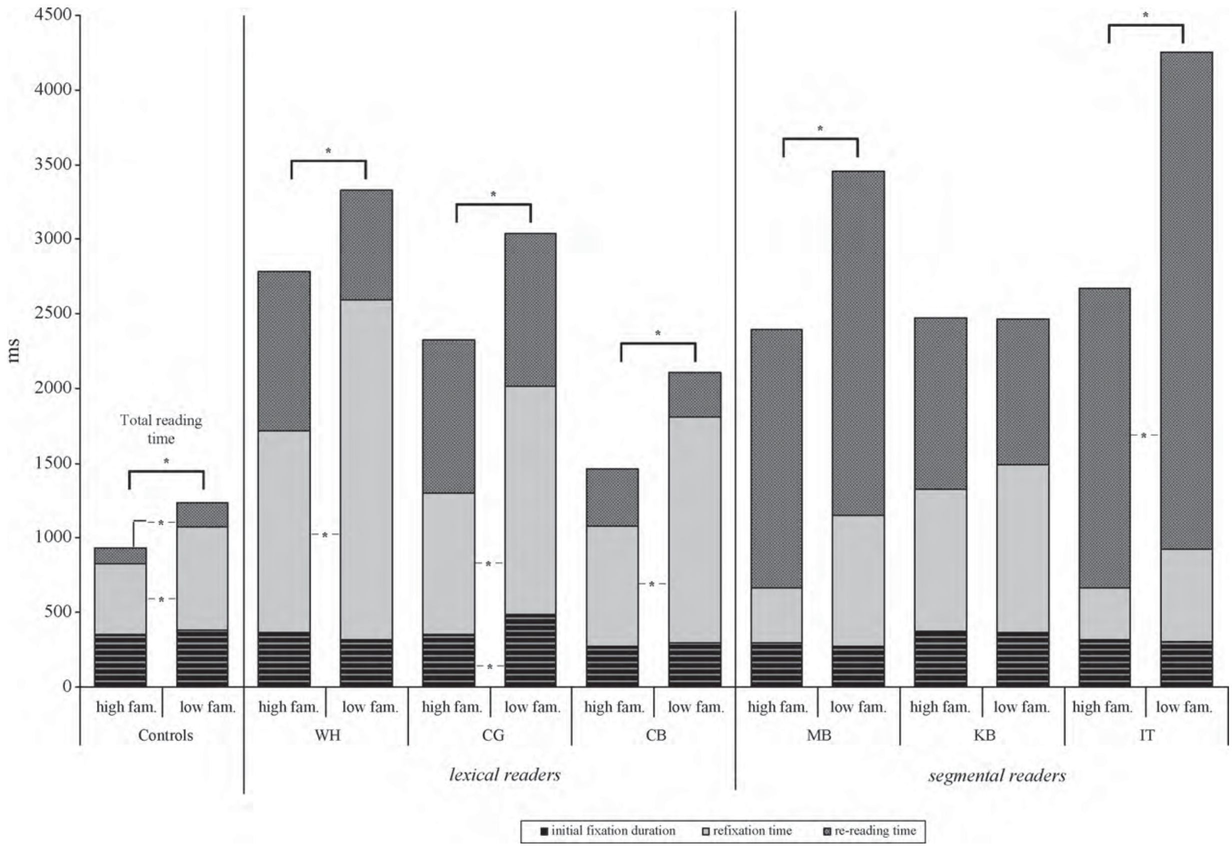

Fig. 8. Stacked Bars of initial fixation duration and refixation time during the first gaze and re-reading time during the following gazes per word familiarity (fam.) for the controls and the six patients (*indicates significant difference between word length, $\alpha = 5\%$; one factorial repeated analysis of variance (ANOVA) for controls, non-parametric Mann–Whitney U-test for monotone trend for estimation of exact p-value for individual patient).

Table 8
Word familiarity effect (mean and standard deviation (SD) for duration in ms and for total number).

n = 64 High familiar (*n* = 32) Low familiar (*n* = 32)		Controls (*n* = 11)		Lexical readers						Segmental readers					
		Mean	SD	Patient WH		Patient CG		Patient CB		Patient MB		Patient KB		Patient IT	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean fixation duration (ms) in the first gaze	High familiar	328	57	340	69	383	169	285	72	297	177	424	220	304	165
	Low familiar	333	63	386	102	448	167	318	79	266	115	393	142	278	117
	p-Value*	0.565		0.046		0.089		0.011		0.313		0.482		0.471	
Total number of fixations in the first gaze	High familiar	2.82	0.58	4.11	3.15	3.16	2.45	4.00	1.84	2.36	2.18	3.23	2.33	2.30	1.66
	Low familiar	3.49	0.79	6.60	3.94	4.77	3.07	5.88	2.50	4.26	4.53	3.61	3.09	3.39	3.16
	p-Value*	<0.001		0.030		0.006		<0.001		0.098		0.378		0.185	

* Values of patients refer to (non-parametric) Mann–Whitney *U*-test for monotone trend for estimation of exact *p*-value.
p-Values of controls refer to one factorial repeated measure of analysis of variance (ANOVA).

specific dyslexic subtypes. Based on typical reading errors we identified two types of dyslexic readers. Two patients (MB and KB) were classified as segmental dyslexia, and two (CG and WH) as lexical dyslexia. In two further patients (IT and CB) there were too few errors for clinical classification; they were considered cases of residual dyslexia. However, their oculomotor behavior characterized one as segmental reader (IT) and one as lexical reader (CB). By segmental dyslexia we refer to a reading impairment in which a segmental reading strategy is pathologically preferred, leading to sublexical phonological errors both in real word and pseudoword reading and which is affected by the length of the stimuli. In contrast, lexical dyslexia is prototypically characterized by a whole word reading strategy leading to word confusions with semantic, phonological or visual similarity to the target and which is affected by the frequency/familiarity of the stimuli. This distinction of segmental and lexical dyslexia overlaps with the classical distinction of surface and deep dyslexia (Coltheart, 1980a, 1980b; Patterson et al., 1985). Clinically, intermediate forms are frequently encountered. In previous research, phonological dyslexia was described as a symptom complex that combines features of surface and deep dyslexia such that both segmental and lexical errors are present (Coslett, 2000). Thus, in clinical samples lexical and segmental reading can be expected to co-exist, and preference for one reading strategy is more likely for segmental reading. This was certainly true in the present patient sample.

One central research question of this study was whether and how the patterns of eye movements observed in our patients would converge with the linguistic classification with regard to the two dyslexic subtypes. Eye movement patterns have been well documented for normal readers and have been proven to be highly informative with regard to oculomotor and linguistic mechanisms mediating reading (e.g. Rayner, 1998). Relevant eye movement parameters are fixations and saccades that make up the first gaze on a word, i.e. the first reading pass until the eye is moved to the next word. Several gazes occur when the word is revisited. We expected that both spatial and temporal parameters of eye movements as established for normal reading would characterize the specific behavior in acquired central dyslexia.

Indeed, as shown for the first time in this study, the measurement of eye movements can provide further evidence to the distinction between segmental and lexical word reading in acquired central dyslexia. Most indicative are spatial parameters, namely the distribution of fixation positions on a word. In the three lexical readers, the initial saccade into a new word tended to land about halfway between the beginning of the word and the word center just as in normal readers. This was repeatedly reported in the literature under the notion of “preferred viewing position” (O’Regan, 1990; Rayner, 1979). In the three segmental readers, initial saccade landing sites were shifted to the beginning of target words, i.e. to the first letter or even to the empty space before the word. This discrepancy was also found when considering the distribution of all fixation positions within target words, including refixations and re-readings. Here the lexical readers tended to show normal bell-shaped distribution patterns in contrast to essentially flat distributions found for segmental readers.

This pattern of results in spatial parameters is in accordance with the psycholinguistic view on two different cognitive reading strategies. Segmental readers have difficulties to access orthographic word forms directly (Coslett, 2000; Howard & Franklin, 1987; Marshall & Newcombe, 1973; Shallice, Warrington, & McCarthy, 1983), and therefore rely on sublexical processing. By sounding out a word phoneme-by-phoneme or syllable-by-syllable, they appear to recognize the word auditorally, i.e. by listening to themselves in order to access the phonological word form. In contrast, lexical readers pursue a direct holistic strategy (Coslett, 2000; Marshall & Newcombe, 1973; Newcombe & Marshall, 1980a, 1980b, 1981; Saffran & Marin, 1977), attempting to perceive the visual word form and to match it with internal orthographic word form information (so-called ‘sight vocabulary’).

These cognitive processes of word processing appear to strongly co-determine the observed oculomotor behavior. Segmental readers rely on segment-by-segment scanning starting at the beginning of a word. Lexical readers start close to the middle of a word in order to perceive it as a whole. Thus, data from reading pathology provide further evidence qualifying and extending the general eye-mind hypothesis (Just & Carpenter, 1980; Kliegl et al., 2006).

In four of the six patients, the notion of two cognitive reading strategies underlying acquired central dyslexia was supported independently by both eye movement behavior and the linguistic error pattern. Landing near the center of a word (preferred viewing positions in normal readers) was associated with lexical word form errors, i.e. whole word confusions in reading aloud, such as ‘Aspirin’ instead of ‘Antiseptikum’ (English ‘aspirin’ instead of ‘antiseptic’). In contrast, landing at the beginning of words was associated with segmental errors, i.e. phoneme and syllable confusions in reading aloud (for example ‘Wenschetreppe’ instead of ‘Wendeltreppe’; English: ‘winding staircase’). Critically, the remaining two patients, although linguistically unspecified due to only residual reading errors, could nevertheless be classified unambiguously as a segmental reader (IT) and as a lexical reader (CB) based on spatial parameters of their eye movements.

One might suggest that the deviation in spatial parameters of segmental readers when compared to normal reading is the result of a primary visuomotor deficit rather than a consequence of the dyslexic impairment. In previous studies visually guided saccades were found to be disturbed (Han, Ciuffreda, & Kapoor, 2004; Rafal, 2006) and shortened in stroke patients (Hund, 1992). Indeed, in two of the three segmental readers, the pathways to the frontal eye fields were affected by the lesion (which was also the case in one of the three patients showing normal spatial fixation behavior). However, in the three segmental readers, despite deviant landing positions of saccades, other spatial parameters of eye movements such as saccade amplitude and relationship between saccade amplitude and speed (so-called main sequence) were all within the normal range of average skilled readers. Thus, the alternative assumption of an underlying contributing oculomotor deficit should be considered with caution for these patients.

In the present study, temporal parameters, in particular frequency and duration of fixations did not clearly distinguish between the two reading strategies underlying central reading disorders. Segmental reading was not generally correlated with more fixations during first pass reading. Only one patient (MB) indeed showed an exceedingly large number of fixations, using an average of nine fixations to scan a 7–8 letter word. The other two segmental readers needed only 2–3 fixations just as found for the normal control group. Among the three lexical readers, one patient (CG) was also indistinguishable from normal readers, but the two other ones (WH and CB) needed significantly more fixations (on the average 4 and 5, respectively). Thus, number of fixations does not per se appear to be indicative of cognitive reading strategies in dyslexia.

How did word length affect the temporal parameters? In normal readers, there was a significant impact. Long words (11–12 letters) needed on the average one fixation more during the first gaze than words of medium length (7–8 letters). Interestingly, only the normal readers showed a frequency-duration trade-off as previously discussed in the literature (Radach & Kennedy, 2004; Rayner, 1998). Here, both, duration of first fixation and mean fixation duration in the first gaze were significantly shorter in long than in medium length words. Similar trade-off effects were not found in the patients with dyslexia, where fixation duration during the first gaze was never affected by word length.

Mean frequency of fixations in the first gaze was affected in the expected direction in two segmental readers (KB and IT) and – unexpectedly – in one lexical reader (WH). The third segmental reader (MB) even showed significantly fewer fixations on long as compared to medium words. However his re-reading time was significantly increased which may suggest that he gave up on first pass reading and attempted to re-read longer words. No other reader with central dyslexia showed this particular behavior.

In contrast to these findings, patients with pure alexia, a peripheral reading impairment, are known to make significantly more fixations per word and to spend more time per fixation than normal readers as recently demonstrated by Behrmann et al. (2001), Rayner and Johnson (2005) and Johnson and Rayner (2007). These authors conclude that more and longer fixations are needed in pure alexia in order to enhance the quality of the input while decoding a word letter-by-letter. This was not generally the case in central dyslexia with segmental reading.

How did word frequency/familiarity affect the temporal parameters? In normal readers there is a significant effect on first gaze duration (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner & Duffy, 1986) and re-reading time. This is exclusively due to higher number of fixation and not to longer durations of initial or mean fixation durations, according to findings reported by Inhoff (1984) and Kliegl, Olson, and Davis (1982). However, Bertram and Hyönä (2003), Inhoff and Rayner (1986), Rayner and Duffy (1986) and White (2008) also reported also significant, single fixation duration effects.

Looking at our patients with central dyslexia, significant word familiarity effects were already evident during first gaze in the lexical but not in the segmental readers. When low word familiarity was contrasted with high word familiarity, only lexical readers showed significantly higher numbers of fixations and longer mean fixation durations as well as longer refixation times after initial fixation duration. Similar familiarity effects were not found in any of the three segmental readers, although in two of them (MB and IT) total reading time was also longer in low- than in high-familiar words. The immediate effect of lexical familiarity in the first gaze of lexical readers was not only obtained for number of fixation like in normal controls but also for mean fixation duration. This supports the assumption that lexical readers predominantly rely on direct access to the orthographic lexicon. Thus, the oculomotor behavior of lexical readers in conditions of dyslexia is in harmony with the eye-mind and the immediacy assumptions as proposed by Just and Carpenter (1980). It is already during the initial fixation (and not only the sum of all first pass fixations) when the lexical reader attempts to achieve lexical access. For our control sample of highly skilled normal readers the difference in difficulty of lexical access between more vs. less familiar words is likely to have been much less pronounced. This may have contributed to the absence of a familiarity effect in mean fixation duration, which is not all that surprising given the mixed results in the literature on sentence reading discussed above.

Prior research on patients with pure alexia revealed a somewhat unexpected word frequency effect in addition to the expected word length effect (Behrmann et al., 2001; Johnson & Rayner, 2007; Rayner & Johnson, 2005). The authors explain this with additional top-down processing while the reader is engaged in effortful letter-by-letter deciphering of the target word, providing enough time for lexical guessing. In segmental central dyslexia such lexical guessing during visual and graphemic letter processing appears to play only a minor role. It is only after substantial progress in grapheme-to-phoneme conversion that word recognition materialized via access to phonological rather than orthographic word representations. Therefore the single fixation is not affected by lexical parameters like familiarity, while, in contrast, in lexical readers it clearly is.

It is interesting to note that prolonged mean fixation durations in first gaze as found both in peripheral dyslexia with letter-by-letter reading and in central dyslexia with lexical reading originate from distinct levels of processing. In lexical reading it is most likely due to mental effort in lexical access, while in letter-by-letter reading it is primarily due to the impact of graphemic letter processing which is specifically impaired. Lexical guessing appears to be a compensatory add-on effect.

A final point of discussion concerns re-reading times. They were expected to reflect self-monitoring in case of linguistic difficulties in lexical access and/or phonological encoding. In normal readers a significant increase in the duration of re-reading was only found for low vs. high lexical familiarity, but not with respect to word length. Apparently only demands for deep lexical processing lead to revisiting a word. With respect to acquired dyslexia we hypothesized a general inflation of re-reading for segmental dyslexia due to higher probabilities of detecting articulation errors in the case of phonological paraphasias in contrast to lexical confusions. Indeed, the re-reading times of two segmental readers (MB and IT) were by far the longest numerically across all conditions. Furthermore, their re-reading times showed a significant influence of psycholinguistic stimulus parameters, word length in MB and lexical frequency/familiarity in IT. The third segmental reader (KB) differed from one lexical reader (CG) only marginally. In general, the re-reading times in all six dyslexic readers were in nearly all instances significantly longer than in the normal controls, i.e. they reflected the severe linguistic processing difficulties these patients experienced when reading aloud.

In future research, we will attempt to improve on some limitations of the present study. First, reading aloud and reading silently should be systematically compared to examine the impact of oral reading on eye movement control, and, more specifically, determine the role of overt word production with regard to the monitoring process. A promising new avenue of research that we are pursuing in this context is the analysis of vocalizations during reading aloud to measure the eye voice span (Buswell, 1920). Furthermore, different modes of stimulus presentation should be explored. Instead of sequences of individual words, the word stimuli could be embedded in full sentences. However, this would necessarily lead to more and different reading errors due to additional morphological and syntactical problems for patients with central dyslexia. We are currently running exploratory studies to determine how many patients within our sample will be capable to produce useful data when attempting to read normal sentences. Finally, it should be mentioned again that the present sample of patients included relatively pure forms of segmental reading together with mixed lexical and segmental reading and residual dyslexia, while purely lexical readers were not present.

6. Conclusion

Overall, the present study attempted to reproduce the distinction of segmental vs. lexical dyslexic reading on the basis of eye movement analyses. A hallmark for the visuomotor side of this distinction lies in the spatial distribution of saccade landing positions, particularly the position of the first fixation on a word. Segmental reading is characterized by initial fixations landing on the beginning of a word, while lexical readers showed preferred landing positions left to the center of a word. Less clear is the impact of the psycholinguistic parameters word length and lexical frequency/familiarity. The three readers with segmental dyslexia cannot be consistently characterized by higher number of fixations during first gaze as a function of increased word length. However, the three readers with lexical dyslexia all showed the expected effects of word frequency/familiarity on both mean duration and frequency of fixations in the first gaze, reflecting their attempts to achieve immediate lexical access. Finally, re-reading time apparently reflected the much higher monitoring demands during oral reading in all participants with acquired central dyslexia.

Ethics

The study has been approved by the ethics committee of the Medical Faculty of the RWTH Aachen University and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All persons gave their informed consent prior to their inclusion in the study.

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