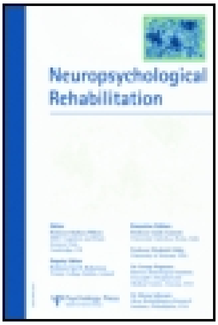

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An eye movement based reading intervention in lexical and segmental readers with acquired dyslexia

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An eye movement based reading intervention in lexical and segmental readers with acquired dyslexia

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Due to their brain damage, aphasic patients with acquired dyslexia often rely to a greater extent on lexical or segmental reading procedures. Thus, therapy intervention is mostly targeted on the more impaired reading strategy. In the present work we introduce a novel therapy approach based on real-time measurement of patients' eye movements as they attempt to read words. More specifically, an eye movement contingent technique of stepwise letter de-masking was used to support sequential reading, whereas fixation-dependent initial masking of non-central letters stimulated a lexical (parallel) reading strategy. Four lexical and four segmental readers with acquired central dyslexia received our intensive reading intervention. All participants showed remarkable improvements as evident in reduced total reading time, a reduced number of fixations per word and improved reading accuracy. Both types of intervention led to item-specific training effects in all subjects. A generalisation to untrained items was only found in segmental readers after the lexical training. Eye movement analyses were also used to compare word

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processing before and after therapy, indicating that all patients, with one exclusion, maintained their preferred reading strategy. However, in several cases the balance between sequential and lexical processing became less extreme, indicating a more effective individual interplay of both word processing routes.

Keywords: Acquired dyslexia; Aphasia; Eye movement; Reading strategy; Therapy.

INTRODUCTION

According to dual-route models, reading is accomplished by two distinct but competitive and interactive processing routes (Coltheart, 2006; 2012; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Houghton & Zorzi, 2003; Kennedy, Radach, Heller, & Pynte, 2000; Rapcsak, Henry, Teague, Carnahan, & Beeson, 2007; for a discussion): A lexical and a sublexical one. Due to their brain damage, patients with acquired dyslexia do not show the well-coordinated interaction of both reading procedures. The predominance of one of these processing routes leads to typical reading errors, providing a basis for clinically discriminating subtypes of pathological reading (Coltheart, 1980; Greenwald, 2000: Morton & Patterson, 1980; Patterson, Marshall, & Coltheart, 1985). More specifically, damage to the sublexical route leads to a complete failure to read pseudo-words, resulting in the standard diagnosis of "deep dyslexia" with the characteristic symptom complex of semantically and visually guided lexical errors, morphological errors and the appearance of a concreteness effect (i.e., concrete words are read significantly better than abstract words). Phonological dyslexia is considered to be a less severe form of deep dyslexia (Crisp, Howard, & Lambon Ralph, 2012; Crisp & Lambon Ralph, 2006; Friedman, 1996; Lambon Ralph & Graham, 2000). The second major form of acquired dyslexia, generally referred to as "surface dyslexia", is the result of damage to the lexical processing route (e.g., Patterson et al., 1985). Here, reading is characterised by attempts to sequentially process words from left to right, with exceptional challenges when reading words with irregular orthography. Patients with surface dyslexia have difficulties in directly accessing orthographic representations. While for the most part reading errors are phonological neologisms in nature, visually guided lexical errors can also be observed.

As an alternative to the dual route account, the reading process may also be described via connectionist approaches (McClelland & Rumelhart, 1981; Plaut, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996). A major difference to dual-route models is the lack of separate processing mechanisms for lexical and sublexical information. According to this view, orthographic, phonological and semantic information are represented in terms of distributed activity within processing units. Every input is processed in a cooperative and competitive interaction among units, in which weighted connections represent the learned knowledge of how the different types of information are related. Skilled reading requires the combined support of all three pathways, i.e., lexical tasks implicate transformations between orthographic, phonological and semantic representations. Within their connectionist approach, Plaut and co-workers (1996; Plaut, 1999) were able to simulate dyslexic reading syndromes and their characteristic error patterns.

Rather than taking sides in the ongoing debate about the best model of reading, we are using the dual route approach as a suitable explanatory framework to characterise both dyslexic impairments and approaches to therapy. Even though the traditional dyslexia classifications have proven extremely useful, it should be noted that in the reality of clinical practice, patients with acquired dyslexia rarely fit neatly into classification of "deep" and "surface" dyslexia, but can vary in severity of their damage to either reading route (e.g., Beaton & Davis, 2007; Berndt, Haendiges, Mitchum, & Wayland, 1996; Huber, 2002; Marshall & Newcombe, 1973; Ska, Garneau-Beaumont, Chesneau, & Damien, 2003; Stadie & Rilling, 2006; Yampolski & Waters, 2002).

So far, treatment of acquired reading disorders has generally attempted to target the dominating form of impairment (Cherney, 2004; Leff & Behrmann, 2008). Based on this principle, two therapy approaches appear to dominate the existing literature. While treatment for patients with a primarily lexical reading strategy is often focused on the consolidation of sublexical reading procedures (Bowes & Martin, 2007; De Partz, 1986; Friedman & Nitzberg Lott, 2002; Kiran, Thompson, & Hashimoto, 2001; Matthews, 1991; Mitchum & Bernd, 1991; Nickels, 1992; Stadie & Rilling, 2006; Yampolsky & Waters, 2002), therapy for segmental readers (surface dyslexia) uses lexical techniques to strengthen orthographic representations (Coltheart & Byng, 1989; Friedman & Robinson, 1991; Scott & Byng, 1989; Stadie & Rilling, 2006; Weekes & Coltheart, 1996). A summary of therapy approaches is provided in Table 1 (for detailed descriptions see, e.g., Cherney, 2004; Leff & Behrmann, 2008).

From the perspective of working to restore healthy reading it appears to be a reasonable strategy to provide training opportunities for both processing routes, even more with patients showing co-existing damage to either route. As an example, a combination of lexical and nonlexical information during treatment has been shown to lead to a substantial reduction in semantic errors (Nickels, 1992; Yampolsky & Waters, 2002), supporting the idea of combined treatment. This principle was also utilised in recent work by Stadie and Rilling (2006) who combined lexical and sublexical-based remediation methods to reactivate both lexical-semantic and segmental processing in a deep dyslexic reader. In their lexical-based procedure, phonological and

TABLE 1
Overview of sublexical and lexical treatment approaches

Paper	*Treatment*	*Outcome*
Sublexical treatment		
De Partz (1986)		Reading improvements on words and pseudowords
Nickels (1992)	Systematic grapheme-phoneme-conversion intervention and phoneme blending in distinct stages	Successful in GPCs, but not in phoneme blending
Mitchum & Berndt (1991)		
Matthews (1991)		
Kiran et al. (2001)		Improvements on trained and untrained items
Yamplsky & Waters (2002)	Simultaneous training of GPCs and blending in words	Successful in CVC words, no generalisation to untrained syllabic structures
Friedman & Nitzberg Lott (2002)	Re-establishing bigraph-biphoneme conversion	No generalisation to untrained words composed of untrained bigraphs
Bowes & Martin (2007)		Improvements on trained and untrained items
Lexical treatment		
Coltheart & Byng (1989)	Pairing irregularly spelled words with visual semantic cues on index cards	Specific treatment effects and generalisation for untrained items
Weekes & Coltheart (1996)		
Scott & Byng (1989)	Homophone training by sentence completion tasks with targets selecting from related homophone, pseudohomophone, visual distractor	Improved reading performance on trained and untrained homophones
Friedman & Robinson (1991)	Practising word reading with ambigous pronunciation of specific letter clusters	Improvement only on trained items
Combined treatment		
Stadie & Rilling (2006)	Lexical approach: Visual priming of the target sublexical treatment: training of GPC and blending	Training specific effects after both approaches; generalisation to untrained items after sublexical approach

GPC = grapheme-phoneme correspondences; CVC = consonant-vowel-consonant pronunciation.

semantic primes preceded the target item to facilitate lexical access. Their sublexical treatment represents a modification of the approach introduced by De Partz (1986), as a computer-based training of grapheme–word associations is followed by grapheme and syllable blending. Results showed significant improvements for trained and untrained items after the non-lexical training, whereas the lexical intervention exclusively led to specific training effects.

In a recent series of studies, Schattka, Radach, and Huber (2010) used eye movement analyses to distinguish between different reading strategies in patients with acquired dyslexia. This work is based on progress made over the last two decades in cognitive science based reading research, where Schattka and co-workers found that analyses of the spatial distribution of fixation positions across words can provide an effective way to determine whether patients with acquired dyslexia use a lexical vs. segmental reading strategy. In lexical readers the initial saccade into a given word tended to land about half way between the beginning of the word and the word centre, just as is the case in normal readers (Rayner, 1979; see Radach & Kempe, 1993, for German data). In segmental reading, however, the initial fixation position was shifted to the beginning of the word or even to the empty space before the word, indicating that segmental readers rely on sequential processing of sublexical units to access orthographic word forms (Coslett, 2000; Marshall & Newcombe, 1973; Shallice, Warrington, & McCarthey, 1983). Other oculomotor parameters, such as number of fixations and fixation durations on a word, were not found to be equally useful in differentiating different cognitive reading strategies in dyslexia (Schattka et al., 2010).

In the present study we follow the principle of combined treatment by stimulating either reading route via the use of both lexical and segmental therapy techniques. An innovative aspect of our work is not only to focus on reading accuracy, but also to extend the scope of the intervention to include the process of word identification in real time. The measurement and analysis of eye movements has become one of the most successful methodologies (see Radach & Kennedy, 2004, 2013; Rayner, 2009, for recent overviews). In the domain of acquired reading disorders this methodology has recently been applied to gain a better understanding of visuomotor and linguistic mechanisms in pathological reading with both peripheral and central disorders (e.g., Ablinger, Huber, Schattka, & Radach, 2013; Behrmann, Shomstein, Black, & Barton, 2001; Johnson & Rayner, 2007; Rayner & Johnson, 2005; Schattka et al., 2010). More specifically, saccade contingent display changes were implemented to induce either a primarily lexical (parallel) or segmental word identification process (see below for details). These strategy manipulations were intended to be instrumental for patients with preferred lexical or sequential reading, strengthening both the better preserved and the more impaired processing route, as well as improving flexibility in utilising both routes.

As is the case with all newly developed treatment approaches, the question arises whether patients may profit more from lexical or segmental training. Based on prior reading intervention studies (Coltheart & Byng, 1989; De Partz, 1986; Scott & Byng, 1989; Stadie & Rilling, 2006; Weekes & Coltheart, 1996), generalisation effects may be observed after segmental as well as lexical therapy. However, this effect might be more pronounced in segmental therapy as it enables the development of more word-independent processing routines (Bowes & Martin, 2007; De Partz, 1986; Kiran et al., 2001; Stadie & Rilling, 2006). As a consequence, pseudo-word reading should be improved after participation in our segmental training approach.

More generally, we sought to determine to what extent and how the new treatment will modify individual reading strategies. This research strategy is informed by our previous work (Ablinger et al., 2013) that provided the first detailed report of changes in word viewing behaviour of a recovering letter-by-letter reader. We described his strategy of information acquisition as a local clustering of letters into sublexical units during a gradual left to right movement across target words. Most importantly, this atypical scanning behaviour became more pronounced over a time period of 15 months, indicating that the patient perfected a word processing strategy that was quite successful but became more and more dissimilar to "normal" reading.

With regard to the present study, two working hypotheses were under consideration. On the one hand it is plausible to predict that a systematic stimulation of both reading strategies leads back to a more balanced interplay of lexical and segmental reading, so that, as a general tendency, reading behaviour becomes more similar to what is usually observed with healthy participants. As an alternative outcome, it appeared possible that specific modifications in reading strategy may result directly after training, so that, as an example, segmental training leads to more serial word processing, especially in patients with predominantly lexical reading.

To summarise, the work reported in this paper examined the effectiveness of an eye movement guided therapy approach, stimulating both lexical and segmental reading procedures. In this context, a refined methodology of spatio-temporal analyses of fixation data (Ablinger et al., 2013) is utilised to provide an adequate metric for objective classification of reading strategies during the time course of recovery.

METHOD

Participants

Eight subjects (mean age = 53 years, range = 32–69 years) with manifest acquired dyslexia participated in this study. All patients were recruited from the Aachen aphasia ward where they received an intensive 7-week aphasia treatment (Huber, Springer, & Willmes, 1993). Patients were invited to take part in the eye movement based reading intervention if they met a predetermined cut-off value in a custom developed reading screening consisting of various reading tasks, including letter naming as well as word (with items varying in frequency, concreteness and word length) and pseudo-word reading. The screening battery had been evaluated in a pilot study with a sample of 38 patients. Performance in word and pseudo-word reading was crucial for inclusion. Patients were not included if they showed severe reading impairment and concomitant severe forms of apraxia of speech and dysarthria, severe neuropsychological restrictions, or aphasia in the acute state. Based on screening results, 14 patients were initially considered for treatment participation. These participants were then asked to read a baseline word sample composed of 400 words. Based on eye movement analyses of these baseline items, six patients were classified as segmental readers and eight as lexical readers (see below for details). Several subjects were excluded from the present study because of a high number of omissions (3), premature termination of therapy (1), application of de-blocking methods when reading (1), and therapy sequence (1). The final sample included the remaining eight patients, with four patients classified as using a primarily segmental reading strategy (JW, SI, WW, SD) and four with a primarily lexical reading strategy (KA, KH, DH, WS). All participants were native German speakers, had normal or corrected to normal vision and were premorbidly right-handed (Edinburgh Inventory; Oldfield, 1971). Type of aphasia was determined based on Aachen Aphasia Test performance profiles (AAT; Huber, Poeck, Weniger, & Willmes, 1983; Willmes, 1985). The aetiology was vascular in seven patients and one suffered from a craniocerebral injury (CCI). A detailed description of the patients is given in Table 2.

According to the standard diagnostic approach, the classification of reading disorders is based on performance in pseudo-word reading and the distribution of reading errors. Looking at our group of participants, three of the segmental readers (JW, WW, SD) would be classified as surface dyslexics and three of the lexical readers (KH, DH, WS) as deep dyslexics. Patients classified as surface dyslexics (segmental readers) named between 30% and 60% of pseudo-word items correctly during baseline sessions. Their word reading mostly resulted in the production of neologistic responses (both with high and low phonological similarity to the target). In contrast, patients classified as deep dyslexics failed completely in pseudo-word reading and the majority of their word reading errors were lexical in nature. Two subjects (KA and SI) did not readily fit into the traditional classification, as both showed a relatively high proportion of neologistic answers in conjunction with poor pseudo-word reading (see also Table 6).

TABLE 2
Biographical details for aphasic patients

	Segmental readers				*Lexical readers*			
Patient	*JW*	*SI*	*WW*	*SD*	*KA*	*KH*	*DH*	*WS*
Gender	M	F	M	F	F	M	M	M
Age in years	48	48	51	51	69	62	63	32
Profession	Landscape gardener	Teacher	Engineer	Designer	Tax counsellor	Tax counsellor	Engineer	Farmer
Years in education	10	17	17	17	10	13	17	10
Aetiology	Left middle cerebral artery infarction with cortical and white matter lesions	Right subarachnoid haemorrhage after ruptured bifurcation aneurysm	Left middle and posterior cerebral artery infarction, with secundary thalamus haemorrhage; lesion extended to temporal and occipital lobe	Left middle cerebral artery infarction; large cortical lesions extending in fronto, parietal and temporal lobe and white matter	Left middle cerebral artery infarction, small temporal and parietal lesions extending in white matter	Left middle cerebral artery infarction	Left haemorrhage; lesion extending in frontal, temporal and parietal lobe, white matter and basalganglia	Craniocerebral injury; lesion extending in left fronto temporal lobe and white matter
Visual deficit	Scotoma in the right lower quadrant	No abnormality detected	Right hemianopia	Minimal visual field defect in the right field	No abnormality detected	Minimal visual field defect in right upper quadrant	No abnormality detected	No abnormality detected
Duration post-onset in months	6	10	5	15	6	10	36	24
*Overall severity and aphasia syndrome classification**	Moderate Wernickés aphasia	Severe to moderate non-classifiable aphasia	Moderate anomic aphasia	Moderate Brocás aphasia	Moderate to mild Wernickés aphasia	Moderate Brocás aphasia	Moderate non-classifiable aphasia	Moderate Brocás aphasia

*Allocation to aphasic syndrome by means of a non-parametric discrimination analysis programme (Huber et al., 1983; Habbema, Hermans, & van den Broek, 1974).

Control group

Oculomotor and reading performance measures were compared with a control group ($n = 8$; mean age = 55 years, range = 38–64 years). All participants were right-handed native German speakers, showed normal or corrected vision and had no history of neurological or psychiatric disabilities.

Materials and item selection

A total of 400 potential target words were selected for baseline examination. All of these items were nouns varying in word length from six to nine letters. The item pool included words with high, medium and low frequency which also differed in concreteness. Each participant was asked to read the total set of 400 words twice in reverse order on two consecutive days to establish baseline performance (T1). Based on these data an individual item pool of 150 words was selected so that words that could not be named or showed inflated reading times were included into three 50-items sets, one for both segmental and lexical therapy, and one for a control assessment. Within each participant, these subsets were matched as closely as possible with respect to word length, lexical frequency and concreteness. In a crossover design, intervention started either with the lexical or segmental eye-movement based reading treatment. Each reading intervention took place over a period of 2 weeks (5 days per week), 50 minutes daily. During each training session, 50 training items were read twice in two consecutive runs with randomised order. On the last day of each intervention phase a control test was administered (T2, T3). To this end, reading performance was assessed with 100 items at T2 (containing the trained and untrained item set) and 150 items at T3 (consisting of both trained item sets and the 50 control items).

Lexical and sequential therapy procedures

Our therapy approach included two different methods, aimed at stimulating a lexical vs. segmental reading strategy. Overall, both methods were designed as a word-level reading training with stimuli presented one by one in randomised order on a computer screen. Participants were asked to read aloud each item as quickly and accurately as possible. At the beginning of each session a written and verbal instruction was given along with a set of five practice items, making sure that the procedure was fully understood.

The lexical reading method was designed to stimulate whole word processing. To this end, eye movement contingent display changes were employed to strictly guide fixations towards the word centre. Depending on word length, for every item, a central field of three to four letters was defined and highlighted. This central region was set to start at letter position three to accommodate the fact that in skilled reading the "preferred viewing position"

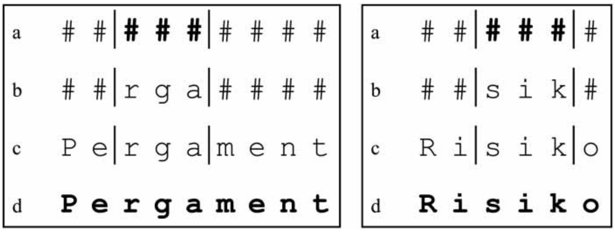

Figure 1. Stages of demasking letters *from centre to periphery* during lexical therapy for word length 6 and 9. After 500 ms of fixation on the centre of the masked string (a), the central letters are revealed (b). Only when these letters are fixated for another 500 ms, the whole word becomes visible. If a fixation is placed outside the central window during this time period, the whole sting will be masked again. Finally, after fixating the fully visible word for a response period of 3000 ms (c), the target word is displayed in blue ink, signalling the end of the trial (d).

(Rayner, 1979; see Radach & Kempe, 1993, for German data) shifts to the left of the geometrical centre as word length increases (see Figure 1a–c). More specifically, the procedure included the following steps: Initially, a central fixation point kept the first fixation position on the centre of the stimulus string. After fixating this position for a fixed period of 500 ms, a masking string with its central field highlighted was presented as shown in Figure 1a. While fixating the word centre, the central mask changed to letters as seen in Figure 1b. After holding the gaze within the central region for another 500 ms the whole word became visible. Critically, as soon as one fixation outside the centre region was detected, all letters outside the region were masked (Figure 1b) and only when the word centre was fixated for another 500 ms did the whole word become visible. This mechanism proved very effective in encouraging patients to hold fixation on the word centre. After keeping the fixation within the central field for 3000 ms (allowing sufficient time for a verbal response), the whole word was finally displayed in blue colour (Figure 1d), indicating the termination of the trial. After each item the patient was given corrective feedback about her/his reading performance (yes/no “target item”).

In the segmental therapy approach, serial processing of target items was guided by a gradual presentation of word segments. Depending on word length, words were displayed in two or three segments. Syllables served as presentation units if they comprised not more than four letters, otherwise smaller letter clusters were determined. All sequences conformed to German phonotactic rules. Similar to the lexical training method, a fixation point kept the first position on the beginning of the stimulus string. After fixating this position for a fixed period of 500 ms, the initial display presented a fully masked string, but this time the initial letters were highlighted (see Figure 2a). After looking at the highlighted letter positions for a period of

a	# # # # # # # # #	a	# # # # # #
b	P e r # # # # # #	b	R i # # # #
c	P e r g a # # # #	c	R i s i # #
d	P e r g a m e n t	d	R i s i k o
e	**P e r g a m e n t**	e	**R i s i k o**

Figure 2. Stages of demasking letters *from left to right* during segmental therapy for word length 6 and 9. After 500 ms of fixation on the initial part of the masked string (a), the first target word segment is revealed (b). When this region is fixated for another 500 ms, the next segment becomes visible (c), followed by a complete demasking after fixating within the first two segments (c). Finally, after displaying the fully visible word for a response period of 3000 ms (d), the target word is displayed in blue ink, signalling the end of the trial (e).

500 ms the first word segment became visible, as illustrated in Figure 2b. In turn, after fixating this initial letter sequence for 500 ms, the next word segment was revealed (see Figure 2c). The complete unmasked word remained on the screen for 3000 ms (Figure 2d), again allowing sufficient time for a verbal response.

After completion of each item the patient was given corrective feedback about his reading performance. Patients were randomly assigned to counter-balanced lists of conditions so that two segmental and two lexical readers started with lexical vs. segmental therapy.

Assessment procedures

To examine changes in reading performance in detail, all participants were asked to read aloud all items in their individual set of target words at three testing points T1 to T3 (we refer to T1 as the mean of baseline 1 and 2) while eye movements and articulation were recorded simultaneously. Note that the untrained item set in the first therapy phase served as control set at T2. Thus, only 100 items were read at T2, whereas all 150 items were read at T1 and T3. In addition to word reading performance, pseudo-word reading was also assessed at all three testing points.

Stimulus presentation, apparatus and eye movement measurement

In all conditions, target words were presented on the computer screen arranged in lines similar to normal sentence reading. This alignment preserves the normal spatial configuration found in text reading so that visual processing demands are close to a natural reading situation. Importantly, the task of reading a sequence of well-controlled nouns avoids higher order post-lexical processing on the sentence and text level that often overwhelms patients with severe reading disabilities. This methodology was used successfully in our laboratory to examine patients suffering from mild to moderate central dyslexia (in the context of aphasia) as well as peripheral dyslexia in the form of letter-by-letter reading (Ablinger et al., 2013; Schattka et al., 2010).

An SR EyeLink 1000 video-based eye tracking system served to record eye movements, based on infrared-light reflection from pupil and cornea at a sampling rate of 1000 Hz. Viewing was binocular but eye movements were recorded from the right eye only. A forehead rest stabilised head position and small head movements were compensated online. The participants' eye position was calibrated using three black dots placed equidistant on a horizontal target line. These 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 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-inch monitor running at a resolution of 1680×1050. Text was presented in non-proportional 15 point Courier font corresponding to 12 pixels per letter horizontally. At a viewing distance of 54 cm, each character subtended approximately 0.5° of visual angle. Blanks before words had the width of one character. After the first calibration, the reading task was demonstrated 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 appeared simultaneously. This was the signal to start reading aloud all eight words in a sequence. When finished, the participant fixated a string of x (xxXxx) at the end of the line and pressed a key on a gamepad which caused the stimuli to disappear. During each session, verbal expressions were digitally recorded on a PC (Adobe Audition, 1.5) for subsequent linguistic analysis. This description of stimuli and procedure applies to both diagnostic and intervention sessions.

Data selection and analysis

A target word was included in data analysis when a saccade landed on at least one of its constituent letters or on the blank space preceding it. Data were organised in terms of pairs of incoming saccades and following fixation durations. Observations containing blinks or fixation durations shorter than 70 ms or longer than 2000 ms, and those outside of three standard deviations of the mean were excluded from analyses. In addition to these standard procedures (Inhoff & Radach, 1998), we also discarded observations with just one fixation per gaze to eliminate cases where eyes had briefly slipped over word boundaries. The first and last word on the line served as fillers and were not considered in any data analyses. In the current study we used total reading time (the summed duration of all fixations within the target word including later re-reading), and total number of fixations to characterise the reading process of our dyslexic subjects (see Ablinger et al., 2013; Johnson & Rayner, 2007; Rayner & Johnson, 2005, for similar data analysis procedures).

We considered five categories of reading errors, semantic errors (with semantic relation to the target item), lexical errors (with and without visual similarity to the target), regularisations, neologistic responses and omissions. Eye movement data were analysed with the EyeMap software (Tang, Reilly, & Vorstius, 2012) and subsequent statistical analyses were computed using SPSS. Performance at different testing points was assessed with the non-parametric Wilcoxon signed-rank test. For the analysis of reading performance between trained and untrained items within one testing point we used the non-parametric Mann-Whitney *U* test. Reading accuracy between testing points was examined with the McNemar test. All statistical analyses are based on one-sided testing.

RESULTS

In the following section we will use oculomotor measures in two different and complementary ways. The reading strategies used by our patients will first be characterised on the basis of how their fixations are distributed over the different letters of the target words during word processing. We will then use the temporal dimension of word viewing behaviour, as expressed in word viewing times to quantify the effectiveness of word reading, with a focus on the changes produced by intensive reading intervention. Finally, to complete the picture, results of error analysis will be used to characterise overt reading behaviour.

Classification of reading strategy using fixation position data

The oculomotor behaviour during reading in the baseline condition served to determine the preferred reading strategy for every subject. In research on normal reading there is a long tradition of characterising local viewing behaviour using the distribution of saccade landing positions (or fixations positions) across words (see Radach & Kennedy, 2013; Rayner, 2009, for recent reviews). As an example, in our control group the distribution of incoming initial saccades has a peak on letter three, which is slightly left to the middle of the target word. This corresponds to the “preferred viewing position” found in skilled readers (Rayner, 1979) and reflects a combination of basic visuomotor constraints and word processing routines (e.g., Radach, Inhoff, & Heller, 2004; Radach & McConkie, 1998).

This method of data analysis has proven useful in our earlier work (Schattka et al., 2010) to describe reading strategies in patients with acquired central dyslexia, as lexical readers typically place their initial fixation slightly left of the word centre (similar to normal readers), while segmental readers tend to start their sequence of fixations at the word beginning. However, for the present sample of patients the exclusive analysis of initial fixations turned out to be insufficient, as differences between suspected lexical and segmental readers were not clear cut. As evident in Figure 3, subjects DH and SI showed atypical distributions with a large peak at letter zero (the space before the first letter), presumably based on a spill-over of fixations aimed at the last letters of the preceding word (see Nuthmann, Engbert, & Kliegl, 2005, for a discussion of misplaced fixations). The single peaks of KA and WS are quite similar to the one observed for JW, precluding a meaningful differentiation between groups on the bases of initial fixation position only.

Clear differences between two groups of readers emerged, however, when we applied a data analysis strategy developed in our research on letter-by-letter reading (Ablinger et al., 2013). More specifically, the total number of fixations was divided into three bins, which allowed examination of shifts in the spatial distribution of fixation positions over the time course of word processing. This procedure identified four readers with a preferred segmental (JW, SI, WW, SD) and four readers with a preferred lexical (KA, KH, DH, WS) word processing strategy.

Focusing on data for T1 (left column) in Figures 4a and b, it is evident that segmental readers started word processing with fixations located more to the

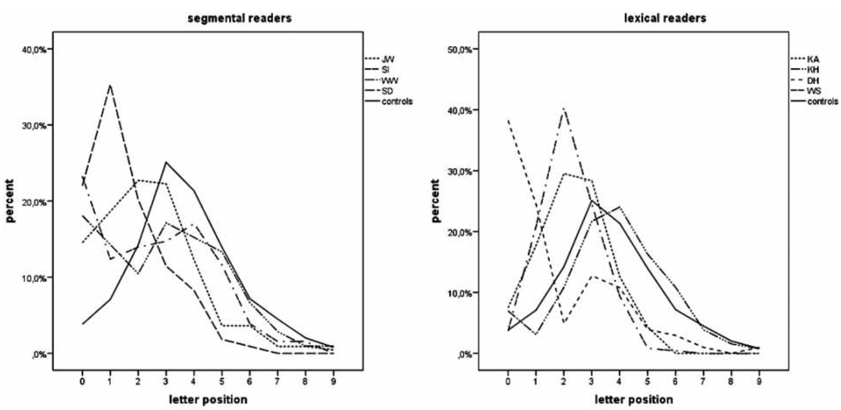

Figure 3. Distribution of landing positions for incoming initial progressive saccades. Letter zero denotes the empty space before the first letter. Note that for reasons of simplicity patients are grouped as segmental vs. lexical readers based on the classification described later in the text.

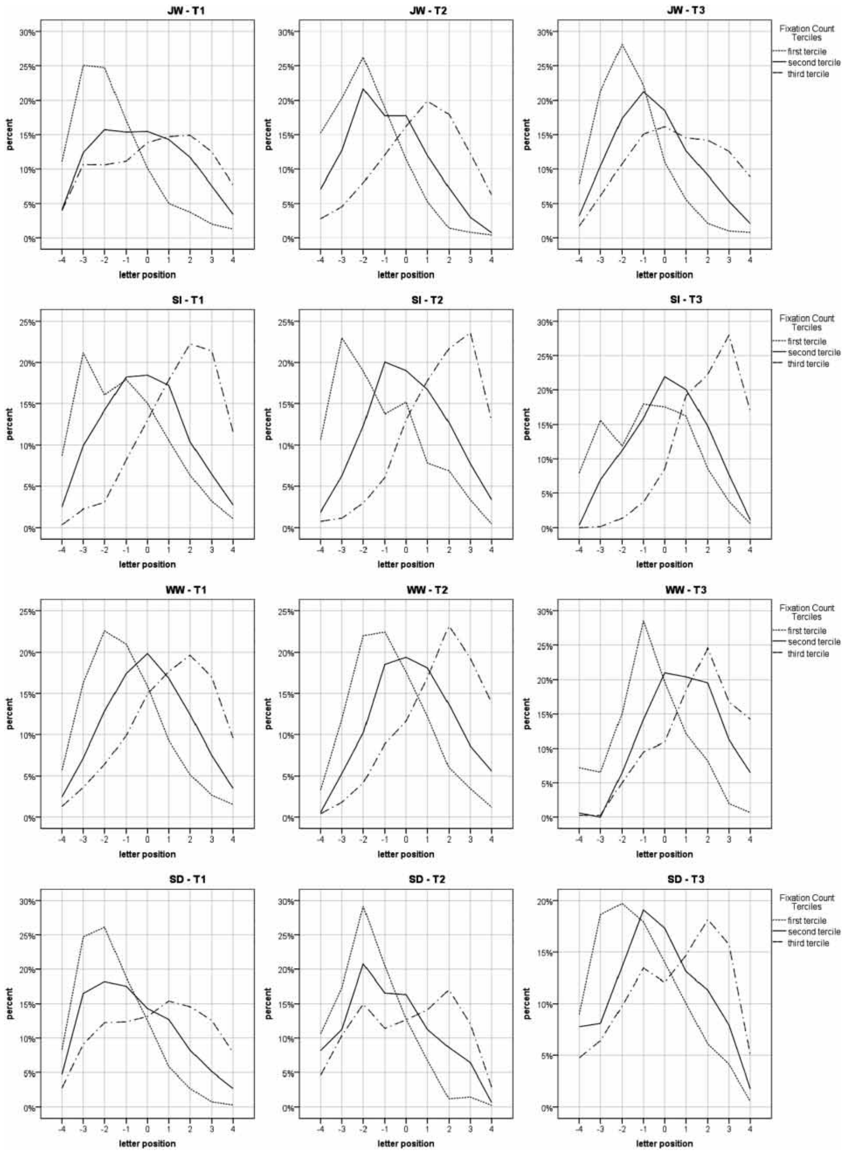

Figure 4(a). Distribution of fixation positions at T1 to T3 partitioned into the first, second and third part of word processing. Distributions are word centre based to allow inclusion of all word lengths. Data for patients classified as segmental readers.

left than lexical readers. There was a gap of at least three letter positions between the peaks of the first and the last third of the fixation distribution and the peaks of all sub-distributions were spatially spread out between

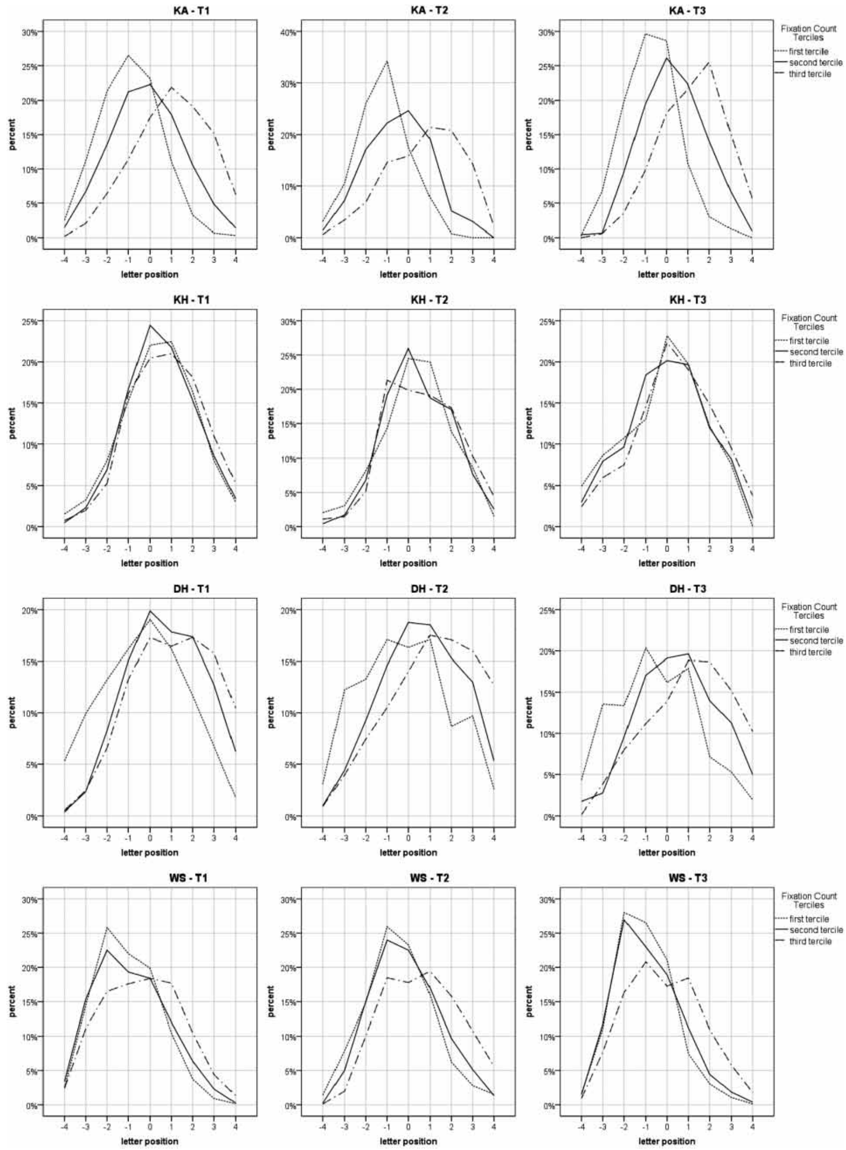

Figure 4(b). Distribution of fixation positions at T1 to T3 partitioned into the first, second and third part of word processing. Distributions are word centre based to allow inclusion of all word lengths. Data for patients classified as lexical readers.

word beginning and word end. This pattern of results strongly suggests that linguistic processing operates on sublexical units, gradually making its way from the word beginning towards the word end.

In contrast, lexical readers started word processing with fixations much closer to the word centre and the spatial distance between the peaks of the first and the last third of the fixation distribution was two characters or fewer. This value corresponds to the small left to right shift observed in patient KA, but the key point is that here all peaks remain within a one-letter distance to the word centre. At first glance WS appears to slightly deviate from an ideal pattern of lexical reading as his early fixations peak two letters from the word centre, but there is almost no difference between the first and second third of fixations and, as a clear difference to all segmental readers, most fixations in the final third of word processing are clearly clustered on or even left of the word centre.

Oculomotor changes over the course of therapy interventions

During the course of interventions, changes in oculomotor behaviour were observed that provide evidence for the development of more refined and automatised reading strategies. Figures 4a and b present the temporal dynamics of fixation positions for T1, T2 and T3. Looking at lexical readers first, KA and WS clearly shifted their fixation positions during the initial phase of word processing about one letter to the right, closer to the preferred viewing location generally found in normal readers. Overall, however, fixation distributions did not change much over the course of reading intervention. Interestingly, segmental readers showed a different pattern with much more pronounced individual changes. In two members of this group (JW, WW) the distribution of fixation positions clearly shifted towards the word centre, and the differences between the three peaks became markedly smaller from T1 to T3, suggesting less segmental reading. SI maintained his typical fixation position at the right end of the word for the final part of word processing at all time points, but moved initial fixations also more towards the word centre. In contrast, SD shifted a large number of final fixations to the end of the word at T3, producing a substantially more pronounced segmental word scanning pattern.

Effects of therapy intervention on word viewing

Overall, aphasic readers had dramatically longer total viewing times and more fixations per word than controls, both in the baseline condition and after therapy intervention ($p < .001$; t-test by Crawford and Howell; see Table 3). However, saccade amplitudes of controls did not differ significantly from those of the patient sample. Most characteristic for the patients' oculomotor behaviour was the ratio between progressive and regressive saccades. Regressions accounted for 39.9% of all saccades as opposed to only 15.5% in the control group. Comparing segmental and lexical reading, segmental readers made substantially more fixations ($p < .001$; Mann-Whitney U),

TABLE 3
Comparision of reading performance between patient sample and controls before and after therapy intervention (standard deviations are given in parenthesis). Reading performance data include correct and incorrect reactions

	T1 Number of Fixations	*T1 Total Reading Time in ms*	*T1 Progressive Intraword Saccades*	*T1 Progressive Interword Saccades*
Controls	2.4 (0.5)	582 (129)	1.4 (0.4)	3.3 (0.5)
Total patient sample	20.1 (11.1)	6943 (3461)	1.0 (0.3)	2.6 (1.3)
Segmental readers	24.6 (11.3)	5755 (3233)	0.8 (0.2)	2.7 (1.3)
Lexical readers	15.5 (10.1)	5130 (2635)	1.2 (0.5)	3.0 (1.3)
	T3 Number of Fixations	*T3 Total Reading Time in ms*	*T3 Progressive Intraword Saccades*	*T3 Progressive Interword Saccades*
Controls	2.4 (0.5)	582 (129)	1.4 (0.4)	3.3 (0.5)
Total patient sample	13.3 (9.8)	4870 (3296)	1.0 (0.4)	2.6 (1.3)
Segmental readers	15.5 (10.1)	5939 (3295)	0.8 (0.3)	2.5 (1.3)
Lexical readers	11.5 (9.1)	3976 (3021)	1.1 (0.4)	2.7 (1.2)

had longer viewing times ($p < .001$), and shorter amplitudes of both intra- and inter-word saccades ($p < .001$).

On a general level, it is apparent that therapy intervention led to improved reading accuracy in all eight subjects. Word identification succeeded faster and was associated with a reduced number of fixations. Table 4 provides individual comparisons of total reading time and total number of fixation per word for T1 vs. T2 and T2 vs. T3 along with adequate test statistics (non-parametric Wilcoxon signed rank tests).

Results for viewing duration and number of fixations specific for item group are given in Table 5. Results for segmental readers are listed first, data for lexical readers follow. Segmental readers JW and WW started with lexical therapy, whereas SI and SD began with the segmental therapy. Lexical reading intervention led to a significant decrease in total viewing time and total number of fixations for trained as well as untrained items in JW, SI, and WW. In addition, JW and WW showed better reading performance for trained (lexical) compared to untrained (segmental) items. Segmental therapy exclusively led to a training effect for trained (segmental) items in JW and WW. However, their total reading time and number of fixations increased significantly for untrained (lexical) items. SI also showed a significant increase in total reading time for untrained items after segmental intervention. SD exclusively presented specific treatment effects for both parameters after both interventions. A general improvement for control items was found in JW and WW at T3 compared to baseline performance. SI just

TABLE 4
Comparision of reading performance between testing points (standard deviations are given in parenthesis). Reading performance data include correct and incorrect reactions

Patient	*Reading Parameter*	*Therapy*	*T1*	*Therapy*	*T2*	*p-value T1T2*	*Therapy*	*T3*	*p-value T2T3*
Segmental Readers									
JW	***Number of Fixations***	baseline	33.7 (6.9)	lexical	16.5 (7.9)	***<.001***	segmental	21.4 (11.7)	=*.169*
	Total Reading Time		10335 (1928)		4885 (2461)	***<.001***		6460 (3618)	=*.129*
SI	***Number of Fixations***	baseline	14.7 (5.7)	segmental	14.6 (5.4)	=*.261*	lexical	10.8 (4.3)	***<.001***
	Total Reading Time		7753 (3171)		8499 (3314)	=*.169*		6457 (2436)	***<.001***
WW	***Number of Fixations***	baseline	33.6 (8.9)	lexical	21 (12.7)	***<.001***	segmental	18.6 (7.6)	=*.075*
	Total Reading Time		10971 (2975)		6877 (4357)	***<.001***		6189 (2769)	=*.108*
SD	***Number of Fixations***	baseline	16.5 (5.6)	segmental	13.7 (9.2)	***<.001***	lexical	13.0 (10.0)	***<.001***
	Total Reading Time		6073 (2018)		5160 (3524)	***<.001***		4768 (3641)	***<.001***
Lexical Readers									
KA	***Number of Fixations***	baseline	14.1 (4.6)	lexical	8.7 (5.3)	***<.001***	segmental	8.9 (5.8)	***=.054***
	Total Reading Time		4650 (1381)		3393 (2133)	***<.001***		3561 (2428)	=*.184*
KH	***Number of Fixations***	baseline	10.0 (4.0)	segmental	7.4 (5.7)	***<.001***	lexical	8.2 (6.0)	=*.125*
	Total Reading Time		4708 (1951)		3592 (3079)	***<.001***		4104 (3044)	=*.075*
DH	***Number of Fixations***	baseline	14.6 (7.0)	lexical	13.2 (7.2)	=*.064*	segmental	11.8 (6.0)	***=.007***
	Total Reading Time		4061 (2045)		3618 (2117)	***=.056***		3203 (1702)	***=.017***
WS	***Number of Fixations***	baseline	21.7 (12.9)	segmental	24.6 (20.9)	=*.489*	lexical	16.1 (13.9)	***<.001***
	Total Reading Time		6161 (3807)		7532 (6708)	=*.312*		4485 (4023)	***<.001***

p-values refer to non-parametric Wilcoxon signed-rank test.

TABLE 5a

Number of fixations and total reading time (in ms) per word as a function of therapy intervention for segmental readers (standard deviations are given in parenthesis). Reading performance data include correct and incorrect reactions

Segmental readers

Patient	*Reading Parameter*	*Itemgroup*	*Therapy*	*T1*	*Therapy*	*T2*	*p-value T1T2 effect size (d)*	*Therapy*	*T3*	*p-value T2T3 effect size (d)*
JW	***Number of Fixations***	**lexical**	baseline	32.1 (6.0)	lexical	14.3 (7.5)	***<.001(2.11)***	segmental	19.7 (11.3)	***<.001 (-0.60)***
		segmental		33.6 (8.1)		18.6 (7.8)	***<.001(1.33)***		15.5 (7.8)	***=.029 (0.35)***
		neutral		33.5 (6.2)					28.8 (11.6)	***=.011 (0.37)***
	Total Reading Time	**lexical**		10178 (1743)		4285 (2431)	***<.001(2.20)***		5954 (3422)	***<.001 (-0.59)***
		segmental		10090 (2162)		5456 (2355)	***<.001(1.41)***		4588 (2476)	***=.028 (0.29)***
		neutral		10387 (1777)					8776 (3550)	***=.004 (0.08)***
SI	***Number of Fixations***	**lexical**	baseline	15.7 (6.3)	segmental	16.0 (5.9)	*=.398*	lexical	9.9 (4.0)	***<.001 (1.03)***
		segmental		14.3 (5.6)		13.2 (4.6)	*=.107*		10.8 (3.8)	***=.001 (0.53)***
		neutral		14.1 (5.1)					11.7 (5.0)	***=.008 (0.33)***
	Total Reading Time	**lexical**		8087 (3406)		9551 (3704)	***=.012 (-0.34)***		6026 (2472)	***<.001 (1.01)***
		segmental		7957 (3149)		7469 (2519)	*=.146*		6249 (1955)	***=.001 (0.49)***
		neutral		7214 (2935)					7096 (2732)	*=.481*

(*Continued*)

TABLE 5a Continued

Segmental readers

Patient	*Reading Parameter*	*Itemgroup*	*Therapy*	*T1*	*Therapy*	*T2*	*p-value T1T2 effect size (d)*	*Therapy*	*T3*	*p-value T2T3 effect size (d)*
WW	***Number of Fixations***	**lexical**	baseline	33.1 (8.6)	lexical	15.7 (7.0)	***<.001 (1.73)***	segmental	19.4 (8.6)	***=.045 (-0.51)***
		segmental		34.1 (9.2)		26.3 (14.6)	***<.001 (0.61)***		15.8 (4.7)	***=.001 (0.66)***
		neutral		33.8 (9.3)					20.7 (8.5)	***<.001 (1.55)***
	Total Reading Time	**lexical**		10643 (2725)		5005 (2336)	***<.001 (1.85)***		6212 (2960)	***=.022 (-0.60)***
		segmental		11329 (3063)		8693 (5030)	***<.001 (0.58)***		5152 (1639)	***=.002 (0.62)***
		neutral		10984 (3137)					7207 (3211)	***<.001 (1.21)***
SD	***Number of Fixations***	**lexical**	baseline	15.7 (5.4)	segmental	16.6 (10.2)	*=.496*	lexical	9.5 (5.5)	***<.001 (0.94)***
		segmental		17.9 (5.5)		10.6 (6.8)	***<.001 (-0.09)***		11.5 (7.7)	*=.319*
		neutral		15.8 (5.6)					18.2 (13.2)	*=.300*
	Total Reading Time	**lexical**		5868 (2014)		6327 (3973)	*=.469*		3416 (1960)	***<.001 (0.94)***
		segmental		6498 (1931)		3935 (2508)	***<.001 (0.88)***		4239 (2909)	*=.340*
		neutral		5825 (2066)					6708 (4679)	*=.315*

p-values refer to non-parametric Wilcoxon signed-rank test; effect size = Cohen's *d*.

TABLE 5b
Number of fixations and total reading time (in ms) per word as a function of therapy intervention for lexical readers (standard deviations are given in parenthesis). Reading performance data include correct and incorrect reactions.

Lexical Readers

Patient	*Reading Parameter*	*Itemgroup*		*T1*	*Therapy*	*T2*	*p-value T1T2 effect size (d)*	*Therapy*	*T3*	*p-value T2T3 effect size (d)*
KA	***Number of Fixations***	**lexical**	baseline	14.4 (4.5)	lexical	7.7 (4.6)	***<.001 (1.32)***	segmental	7.9 (6.0)	*=.499*
		segmental		14.3 (4.5)		9.8 (5.8)	***<.001 (0.73)***		8.1 (5.0)	***=.022 (0.29)***
		neutral		13.6 (4.8)					10.8 (5.9)	***=.002 (0.37)***
	Total Reading Time	**lexical**		4746 (1319)		2875 (1881)	***<.001 (0.79)***		3211 (2510)	*=.181*
		segmental		4652 (1371)		3911 (2260)	***=.009 (0.28)***		3211 (2157)	***=.022 (0.24)***
		neutral		4552 (1471)					4261 (2494)	*=.119*
KH	***Number of Fixations***	**lexical**	baseline	11.0 (3.9)	segmental	8.1 (5.5)	***<.001 (0.44)***	lexical	7.1 (4.4)	*=.421*
		segmental		12.3 (4.8)		9.2 (7.6)	***<.001 (0.39)***		10.3 (6.3)	***=.039 (-0.13)***
		neutral		12.0 (4.3)					10.0 (7.1)	***=.010 (0.27)***
	Total Reading Time	**lexical**		5047 (1774)		3742 (2566)	***=.001 (0.41)***		3701 (2402)	*=.194*
		segmental		5847 (2189)		4647 (4478)	***=.002 (0.28)***		5223 (3357)	***=.032 (-0.11)***
		neutral		6051 (2335)					5044 (3538)	***=.015 (0.26)***

(*Continued*)

TABLE 5b Continued

Lexical Readers

Patient	*Reading Parameter*	*Itemgroup*		*T1*	*Therapy*	*T2*	*p-value T1T2 effect size (d)*	*Therapy*	*T3*	*p-value T2T3 effect size (d)*
DH	***Number of Fixations***	**lexical**	baseline	14.5 (5.7)	lexical	10.8 (5.4)	***<.001 (0.50)***	segmental	11.5 (6.1)	*=.185*
		segmental		14.1 (7.3)		15.4 (8.0)	*=214*		10.3 (4.8)	***<.001 (0.61)***
		neutral		15.2 (7.8)					13.5 (6.7)	*=.167*
	Total Reading Time	**lexical**		4058 (1716)		2959 (1570)	***<.001 (0.49)***		3112 (1786)	*=.159*
		segmental		3901 (2078)		4263 (2385)	*=236*		2855 (1405)	***<.001 (0.59)***
		neutral		4225 (2323)					3643 (1821)	*=.141*
WS	***Number of Fixations***	**lexical**	baseline	22.9 (14.3)	segmental	25.9 (17.0)	*=.156*	lexical	17.4 (16.0)	***=.001 (0.38)***
		segmental		22.0 (12.0)		23.3 (24.2)	*=.164*		15.2 (12.9)	***=.019 (0.44)***
		neutral		20.1 (12.4)					15.6 (12.8)	***=.003 (0.31)***
	Total Reading Time	**lexical**		6507 (4098)		7788 (5317)	*=.102*		4849 (4484)	***=.001 (0.43)***
		segmental		6279 (3505)		7276 (7907)	*=.283*		4240 (3812)	***=.005 (0.54)***
		neutral		5698 (3827)					4367 (3789)	***=.003 (0.30)***

p-values refer to non-parametric Wilcoxon signed-rank test; effect size = Cohen's *d*.

showed a significantly lower rate of fixations for control items after therapy intervention.

Strikingly different results were obtained with lexical readers. In two patients, KA and KH, the first therapy that was applied appeared to be more effective. KA started with the lexical training while KH received segmental therapy first. Both patients showed a significant decrease for trained and untrained items in total reading time and total number of fixations at T2. Moreover, trained items were significantly better processed than untrained items. The second intervention led to a specific training effect in both parameters for KA, whereas KH had a significant increase in total reading time and number of fixations for untrained (lexical) items at T3. DH received lexical training first, followed by segmental training. After both therapy phases, a specific training effect was found in the reduction of total reading time and total number of fixations. In all three subjects total reading time and total number of fixations did not differ between trained and untrained items after the segmental approach (Mann-Whitney *U* test). WS received segmental training first. The training led to a numerical increase in total reading time and number of fixations at T2. However, trained (segmental) items were significantly better processed. Significant improvements in both parameters were found at T3 for trained and untrained items. It should be noted that the increase in total reading time and number of fixations at T2 may be attributed to the enormous number of produced omissions in baseline.

Overt reading accuracy

Word reading and pseudo-word processing accuracy was determined and reading errors classified at all three testing points (see Table 6). None of the patients showed improvements in pseudo-word reading. However, all significantly increased their reading accuracy over the course of intervention, while, interestingly, the relative frequency of the different classes of errors did not substantially change. In all four segmental readers the main error type was segmental phonological errors, invariably leading to neologistic responses. A minor part of their error distribution included lexical errors. Pseudo-word reading was done with some success, except for SI, who showed considerable difficulties in this task.

As evident in Table 4, the lexical readers did not produce an equally homogenous pattern of errors. KH and DH predominantly made lexical errors, but also a fair number of neologistic responses and omissions. In addition, KH made some semantic errors. KA, on the other hand primarily showed neologisms, and a smaller number of lexical errors. In addition to a large number of omissions at baseline, WS also showed neologistic, lexical and semantic errors. As mentioned above, the frequency of all error types was reduced

TABLE 6
Accuracy and error distribution in word reading. Accuracy for pseudo-words

	Test	*Words* Accuracy (%)	Neologisms (%)	Lexical Errors (%)	Semantic Errors (%)	Regularisations (%)	Omissions (%)	*Pseudowords (n = 80)* Accuracy (%)
Segmental Readers								
JW	T1 (n=150)	0 (0)	136 (90.7)	14 (9.3)	0	0	0	23 (28.8)
	T2 (n=100)	49 (49)	47 (47)	4 (4)	0	0	0	31 (38.8)
	T3 (n=150)	105 (70)	40 (26.7)	5 (3.3)	0	0	0	18 (22.5)
SI	T1 (n=150)	0 (0)	141 (94)	7 (4.7)	0	0	2 (1.3)	5 (6.3)
	T2 (n=100)	22 (22)	74 (74)	4 (4)	0	0	0	8 (10)
	T3 (n=150)	44 (33.3)	100 (66.7)	6 (4)	0	0	0	7 (8.8)
WW	T1 (n=150)	36 (24)	92 (61.3)	20 (13.3)	0	2 (1.3)	0	40 (50)
	T2 (n=100)	90 (90)	7 (7)	3 (3)	0	0	0	32 (40)
	T3 (n=150)	139 (92.7)	7 (4.7)	4 (2.7)	0	0	0	36 (45)
SD	T1 (n=150)	32 (21.3)	96 (64)	16 (10.7)	0	5 (3.3)	1 (0.6)	49 (61.3)
	T2 (n=100)	69 (69)	24 (24)	7 (7)	0	0	0	45 (56.3)
	T3 (n=150)	123 (82)	22 (14.7)	5 (3.3)	0	0	0	43 (53.8)

(*Continued*)

TABLE 6 Continued

		Words						*Pseudowords (n = 80)*
	Test	*Accuracy (%)*	*Neologisms (%)*	*Lexical Errors (%)*	*Semantic Errors (%)*	*Regularisations (%)*	*Omissions (%)*	*Accuracy (%)*
Lexical Readers								
KA	T1 (n=150)	0 (0)	134 (89.3)	13 (8.6)	2 (1.3)	0	1 (0.6)	9 (11.3)
	T2 (n=100)	39 (39)	55 (55)	6 (4)	0	0	0	8 (10)
	T3 (n=150)	55 (37.7)	92 (61.3)	3 (2)	0	0	0	2 (2.5)
KH	T1 (n=150)	0 (0)	32 (21.3)	74 (49.3)	8 (5.3)	0	36 (24)	1 (1.3)
	T2 (n=100)	34 (34)	19 (19)	37 (37)	0	0	10 (10)	2 (2.5)
	T3 (n=150)	76 (50.7)	17 (11.3)	40 (26.7)	1 (0.6)	0	1 (0.6)	1 (1.3)
DH	T1 (n=150)	16 (10.7)	41 (27.3)	78 (52.0)	1 (0.6)	0	14 (9.3)	1 (1.3)
	T2 (n=100)	48 (48)	16 (16)	33 (33)	1 (1)	0	2 (2)	1 (1.3)
	T3 (n=150)	68 (45.3)	29 (19.3)	35 (23.3)	1 (0.6)	0	17 (11.3)	0
WS	T1 (n=150)	0 (0)	34 (22.7)	27 (18)	13 (8.7)	0	80 (53.3)	1 (1.3)
	T2 (n=100)	48 (48)	16 (16)	11 (11)	6 (6)	0	19 (19)	0
	T3 (n=150)	67 (44.7)	29 (19.3)	23 (15.3)	5 (3.3)	0	26 (17.3)	3 (3.8)

during the intervention, reproducing roughly the same distribution, except for omissions, which were reduced over-proportionally.

DISCUSSION

In the present study we report on an innovative eye movement contingent reading intervention with the goal to stimulate and optimise reading strategies in eight aphasic patients. The fundamental idea of this approach is to use real-time feedback on reading behaviour to control the visual availability of letter information. More specifically, in the sequential training method, a gradual presentation of word segments was used to support sequential processing. In contrast, the lexical training method forced readers to keep their gaze at the centre of the target word so that that all letters were visible, provoking a more lexical strategy of word processing.

In the focus of interest was the question of whether or not both eye movement based training approaches would yield a comparable outcome on reading performance (as measured by eye movement parameters) in dyslexic readers with different underlying reading strategies. After an intensive four week reading intervention, all eight patients showed remarkable improvements in reading performance including a substantially reduced total reading time, a smaller number of fixations per word and improved reading accuracy.

Both interventions led to item-specific training effects in all participants. These specific beneficial effects on reading performance might also have been attained due to repeated runs and corrective verbal feedback, which is associated with a general activation of visual, semantic and phonological information (Howard, 1986). Starting with the classic architecture of McClelland and Rumelhart (1981; Plaut, 1999; Plaut et al., 1996), interactive activation models of word recognition have postulated a permanent interaction of letter and word level due to bottom-up and top-down processes (see Reilly & Radach, 2006, for an extension to continuous reading). Therefore, lexical as well as segmental therapy may have succeeded in equal measure in the stabilisation of lexical entries on word level.

However, closer examination of the results and comparison of both training methods provide solid evidence for specific strategy-dependent therapy efficiency. In addition to improvements with trained items, three segmental readers (JW, SI, WW) also demonstrated a generalisation to untrained items after the lexical therapy intervention; total reading time and number of fixations were significantly reduced. On the other hand, segmental therapy led to a significant decline in performance with untrained lexical items. Although not statistically significant, patient SD also showed a numerically similar pattern. It appears reasonable to conclude that in these patients a segmental reading approach strengthened pathological sequential reading and thus led to increased cognitive effort with untrained items.

Lexical readers did not exhibit an equally consistent pattern, as in only two patients (KA, KH) was a generalisation to untrained items after the first reading intervention found. The type of intervention was obviously not a determining factor for this result, since it was lexical therapy in the one case and segmental therapy in the other case. Looking more closely, there is one interesting similarity in the results of lexical readers after the segmental approach. In three patients (KA, KH, DH) we did not find a significant difference in total reading time between trained and untrained items despite the existing treatment effect. Thus, untrained lexical items remained relatively stable (or in the case of KH improved in a way similar to trained items) so that reading performance of trained and untrained became similar.

In summary, although both lexical and segmental therapy approaches resulted in specific treatment effects in all patients, lexical therapy turned out to be more effective for segmental readers, as it lead to a generalisation to untrained items. On the other hand, segmental intervention appeared to be particularly effective for lexical readers, because word processing efficiency (as measured via eye movements) for trained and untrained items converged, without any decline in reading aloud performance. These results should not have been influenced by therapy sequence, since the arrangement of conditions was systematically varied.

Patient WS does not appear to fit with the observed pattern of results for lexical reading. The explanation for this seeming disagreement is that at baseline WS often produced omissions that are associated with short viewing durations. As a consequence of the reading training intervention the number of abandoned trials was substantially reduced, leading to a paradoxical increase in total reading time and number of fixations. Critically, there was a significant item-specific training effect after the first treatment phase, and, after the second phase, significant reading performance was even transferred to untrained items.

We had assumed that segmental therapy would lead to a generalisation to untrained items to a greater extent than the lexical treatment. The segmental approach should result in an improved grapheme–phoneme conversion and synthesis (Bowes & Martin, 2007; De Partz, 1986; Kiran et al., 2001; Stadie & Rilling, 2006), paving the way for transfer to untrained items (but see also Friedman & Nitzberg Lott, 2002; Mitchum & Bernd, 1991; Nickels, 1992; Yampolsky & Waters, 2002). Except for one subject (KH), we did not find any transfer to untrained items after segmental therapy. In the same way pseudo-word reading performance did not change in any of the participants. This somewhat unexpected result may be attributed to the fact that, in contrast to conventional training procedures with sublexical reading (DePartz, 1986; Friedman & Nitzberg Lott, 2002; Mitchum &

Bernd, 1991; Nickels, 1992; Stadie & Rilling, 2006; Yampolsky & Waters, 2002), our focus in the segmental therapy was not on an explicit training of grapheme–phoneme conversion. In our display change based training technique the reader's eye movements were instrumental for the demasking of the following word segment. In other words, the driving force of progress in training was linguistic processing as it occurred and not its result, the correct articulation of a word segment. As mentioned above, a transfer of improved reading performance to untrained items was found in three segmental readers after lexical therapy. In skilled normal readers whole word recognition is an automatised and highly overlearned process (see Cherny, 2004, for a comparative discussion). It may be the case that this whole word procedure was also more attractive to our subjects than a predetermined segmental procedure that is not perfectly tuned to someone's individual processing routines. The lexical eye movement guided therapy approach might have reactivated residual capacities of lexical whole word reading even in those patients who could not access highly automatised processing routines. This hypothesis is in line with Weekes and Coltheart's (1996) suggestion that their lexical treatment for irregularly spelled words altered the operation of the word recognition system so that even untrained items improved. Based on the assumption that lexical and sublexical processes work in parallel and support each other to access orthographic representations from the lexicon (Hillis & Caramazza, 1991, 1995; Rapp, Eppstein, & Tainturier, 2002), the lexical approach might well have facilitated sublexical processing as well. These considerations are in line with the tentative conclusion that our segmental eye movement guided training approach may not have activated both processing procedures to the same dimension as the lexical approach.

We used innovative eye tracking methodology to quantify the word viewing behaviour of our participants, developing a new technique for identifying their preferred reading strategy resulting from their brain damage. More specifically, we divided the total number of fixations per target word into three equal bins and computed the resulting distributions of fixation positions. Comparing these sub-distributions allows examination of the shifting of fixation positions over the time course of word processing. Ideally, a patient using a sequential reading strategy should gradually move fixations through the word from left to right, resulting in three spatially distant peaks in position distributions spread out between word beginning and word end. In contrast, an ideal lexical reader should produce sub-distributions with fixation positions accumulating close to the word centre. Using this line of reasoning, our sample of eight patients could be unequivocally divided into two sub-groups with preferred sequential vs. lexical reading strategy. However, even when a preference is apparent, many patients show some degree of impairment with regard to both reading routes (Beaton & Davis, 2007; Huber, 2002; Stadie & Rilling, 2006; Yampolski & Waters, 2002). Looking closely at Figures 4a and b, it appears that our approach reflects the degree to which the alternative processing route may co-determine performance. As an example, the fixation position distributions in Figure 4b suggest that patients KA and WS do not use a purely lexical processing strategy, as there is also an element of seriality in their fixation pattern.

Traditionally, word reading strategy is assessed via linguistic error analysis of oral word reading. The production of phonological neologisms is taken to indicate a segmental reading strategy. On the other hand, the production of word substitutions based on visual, lexical, semantic or morphological similarity is assumed to be indicative of a lexical reading strategy (e.g., Buchanan, McEwen, Westbury, & Libben, 2003; Coltheart, 1980; Rastle, Tyler, & Marslen-Wilson, 2006). Examples from our patient sample can serve to illustrate the fact that this line of reasoning can be problematic. Patient KA produced in 89.3% of all words phonological neologistic responses, suggesting, according to linguistic error analysis, a strongly segmental reading strategy. In contrast, eye movement analyses showed largely symmetric and relatively steep landing site sub-distributions peaking near to the word centre. Consequently, KA was classified as a primarily lexical reader. However, as discussed above, over time there is also a slight left-to-right shift in these landing site distributions, suggesting some sequential processing. Consequently, the eye movement based assessment not only precluded a misclassification as a strongly segmental reader, but also allowed the specification of a combination of dominant lexical with additional segmental word processing.

An important topic in current debate on reading intervention for patients with acquired dyslexia is whether performance improvements result from a change or a refinement in reading strategy. As an example, letter-by-letter readers tend to maintain key elements of the reading strategies developed in response to their initial impairment over the course of recovery (Ablinger et al., 2013; Ablinger & Domahs, 2009; Arguin & Bub, 1994; Beeson, 1998; Behrmann, Black, & Bub, 1990; Behrmann & McLeod, 1995; Bohn & Stadie, 2005; Friedman & Alexander, 1984; Friedman & Nitzberg Lott, 2000; Gonzalez Rothi & Moss, 1992; Lott, Friedman, & Linebaugh, 1994; Nitzberg Lott & Friedman, 1999; Sage, Hesketh, & Ralph, 2005).

In the present study we found that except for one patient (DH), all subjects maintained their preferred reading strategy after reading treatment. Interestingly, lexical and segmental readers showed differences in their pattern of improvement. Segmental readers exhibited changes in their overall fixation distributions so that fixation positions generally shifted towards the word centre. However, in all cases, distinct peaks of sub-distributions remained the hallmark of sequential word reading.

In contrast, therapy-based improvements of lexical readers materialised primarily in their initial landing position so that the first fixation on the word shifted approximately one position to the right. Word processing started comparable to healthy readers at letter position three with two subjects (KA, WS).

Only one patient appeared to have changed his reading strategy as a consequence of therapy. DH switched from a clearly lexical to an explicit sequential reading procedure. It is remarkable that even after lexical intervention he preferred to work through the word in a sequential manner, which became even more pronounced after the second, segmental, intervention. Given the considerable reduction of lexical errors at both testing points T2 and T3, we assume that the change in reading strategy was motivated by more successful sequential reading compared to the frequent lexical guessing errors observed at baseline condition. Even at T3 DH was still considerably impaired, but lexical and neologistic responses were relatively balanced.

In most cases individuals with acquired reading disorders primarily rely on either a lexical or segmental reading strategy (Coltheart, 1980; 1996; Morton & Patterson, 1980; Newcombe & Marshall, 1981; Patterson et al., 1985; Rapcsak et al., 2007). As observed in the case of DH, a further benefit of our treatment is the opportunity to show subjects that approaches other than the one they primarily use may be even more beneficial to identify the target. Even for patients who do not rely purely on one processing strategy, as seen in KA and WS, an additional strengthening of the segmental processing component may have contributed substantially to better reading accuracy after therapy.

In conclusion, our innovative eye movement guided lexical and segmental therapy approach represents an objective therapy method in which word reading performance could be substantially improved and even optimised within a brief period. The present study also introduces a novel approach to examine and classify moment-to-moment word processing in dyslexic patients, contributing to a better understanding of impairments and the dynamics of recovery and therapy interventions. Our results point to important implications for approaches in therapy. At first sight dyslexia-type specific effects appear to provide a solid base to guide decisions on the optimal therapy for patients with acquired dyslexia. However, especially for lexical readers, there are two important aspects of our data suggesting that the combined treatment approach may be particularly promising in contributing to improved reading performance (Hillis & Caramazza, 1991): The absence of a generalisation effect and the combined processing strategies as revealed by fixation position analyses. In light of these finding it remains an issue for future work to determine which proportion and sequence of specific treatment types is likely to be most effective.

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