

Reviews and perspectives

The significance of visual information processing in reading: Insights from hemianopic dyslexia

Susanne Schuett^{a,*}, Charles A. Heywood^a, Robert W. Kentridge^a, Josef Zihl^{b,c}^a Department of Psychology, University of Durham, UK^b Department of Psychology, Neuropsychology, Ludwig-Maximilians-University Munich, Germany^c Max-Planck-Institute of Psychiatry, Germany

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ABSTRACT

We present the first comprehensive review of research into hemianopic dyslexia since Mauthner's original description of 1881. We offer an explanation of the reading impairment in patients with unilateral homonymous visual field disorders and clarify its functional and anatomical bases. The major focus of our review is on visual information processing, visuospatial attention and eye-movement control during reading. An advanced understanding of the basis of hemianopic dyslexia and its rehabilitation also increases our knowledge about normal reading and its underlying neural mechanisms. By drawing together various sources of evidence we illustrate the significance of bottom-up and attentional top-down control of visual information processing and saccadic eye-movements in reading. Reading depends critically on the cortical–subcortical network subserving the integration of visual, attentional and oculomotor processes involved in text processing.

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* Corresponding author at: Department of Psychology, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, UK. Tel.: +44 191 3343268; fax: +44 191 3343241.

E-mail address: susanne.schuett@durham.ac.uk (S. Schuett).

1. Introduction

Reading is a complex skill which can be disturbed at any of its visual, lexical–semantic and phonological processing stages. A wide variety of quantitatively and qualitatively different reading disorders following brain injury has been identified (for reviews, see Ellis & Young, 1996; Hillis & Caramazza, 1992; Shallice, 1988). Acquired impairments of reading in subjects with previously well-established reading skills immediately draw to mind the aphasic reading disorders which involve disturbances of lexical and/or post-lexical processes. These higher-level reading disorders (central dyslexias) rank high in neuropsychology's research agenda and have substantially contributed to the development of models of the normal reading process.

Unfortunately, the acquired lower-level reading disorders, which involve impairments of pre-lexical (visual) processes, have been largely neglected. These so-called peripheral dyslexias arise from disturbances at the more peripheral levels of text information processing. Visual field disorders, deficits of visual acuity, spatial contrast sensitivity and visual adaptation, disorders in visuospatial perception, spatial restriction of the field of visual attention (a prominent symptom of visual neglect and Balint's syndrome), visual agnosia, and visual illusions and hallucinations can all impair reading at various levels of visual processing (Baylis, Driver, Baylis, & Rafal, 1994; Behrmann, Moscovitch, Black, & Mozer, 1990; Behrmann, Shomstein, Black, & Barton, 2001; De Luca, Spinelli, & Zoccolotti, 1996; Hess, Zihl, Pointer, & Schmid, 1990; Zihl, 1989, 1995a; Zihl & Kerkhoff, 1990; Zihl & von Cramon, 1986). Although the peripheral dyslexias have been attracting increasing attention recently, the chief focus has been on the clinical syndromes of neglect dyslexia and pure alexia or visual agnosia for letters.

Surprisingly, hemianopic dyslexia, the most elementary and frequent peripheral dyslexia (present in ~15% of patients in neurological rehabilitation centres, see Kerkhoff, 1999; Prosiegel, 1988), is hardly considered in reviews or text books dealing with peripheral dyslexias (e.g. Ellis & Young, 1996; Riddoch, 1991; Shallice, 1988). It perhaps counts as the most important visual impairment following brain injury affecting the patients' occupational and daily life as a pronounced visual handicap (Papageorgiou et al., 2007; Zihl, 2000). Reading becomes so laborious that many patients give up recreational reading; if reading is essential for their occupation, continuing employment may be at risk (Leff, Spitzyna, Plant, & Wise, 2006). Hemianopic dyslexia (also called hemianopic alexia) is an acquired reading disorder in which 80% of patients with homonymous visual field defects affecting parafoveal (and foveal) vision have severe reading difficulties despite intact language functions (Zihl, 2000). In these patients, word identification and the ability to plan and guide reading eye-movements is disturbed (McDonald, Spitzyna, Shillcock, Wise, & Leff, 2006; Spitzyna et al., 2007; Zihl, 1995a).

This article offers the first comprehensive review of research into hemianopic dyslexia. We explain the nature of hemianopic dyslexia and clarify its functional and anatomical bases. Furthermore, we consider what hemianopic dyslexia can tell us about normal reading and its neural basis. In this manner we hope to provide a coherent framework for future work.

Our review is organised into six sections. First, we give a brief survey of the themes relevant for our critical examination of the findings from hemianopic dyslexia research by introducing reading as a complex skill entailing coordinated visual information processing, eye-movement control, visuospatial attention and linguistic processing (Section 2). In Section 3, we describe the features of homonymous visual field disorders and review the findings from hemianopic dyslexia research since Mauthner's original description of 1881. In Section 4, we demonstrate the significance of

parafoveal vision for reading by discussing the effects of unilateral homonymous parafoveal visual field loss on word identification and oculomotor control in reading, both at the behavioural and neural level. Examining the anatomy of hemianopic dyslexia in Section 5 shows that parafoveal visual field loss in itself cannot completely account for this reading impairment. Section 6 discusses a compensatory treatment approach for rehabilitating hemianopic dyslexia, which reveals important insights into the functional plasticity of the visual, attentional and oculomotor systems involved in text processing. In Section 7, we provide a synopsis of all sources of evidence that demonstrates the important insights studying hemianopic dyslexia generates into the normal reading process and its neural basis, which may be useful in informing theories and models of reading and eye-movement control.

2. Reading: vision, attention, eye-movements, and language in (inter-)action

Poppelreuter (1917/1990) remarked that "it should theoretically be possible (...) to conclude a priori that a hemianopia (...) must impair reading" (p. 223) and regarded a detailed consideration of theories of visual information processing and eye-movements in normal reading as essential. However, he also firmly believed that hemianopic dyslexia could not be explained as "merely a consequence of (...) hemianopia" (p. 226). Thus, the basis of hemianopic dyslexia may not be purely visual and we therefore consider the visual, attentional, oculomotor and language processes involved in normal reading and their underlying neural mechanisms.

2.1. Eye-movements and visual information processing in reading

Reading is the process of understanding written language. This requires our eyes to move in such a way as to allow for the extraction of spatially distributed visual information which is in harmony with the speed of comprehension (Findlay & Gilchrist, 2003). The eyes follow a typical scan path across the text, in the direction depending upon the language of the text (i.e. from left-to-right and from top-to-bottom for Western cultures). Plotting eye position against time reveals a staircase pattern as saccadic eye-movements regularly alternate with periods of fixations. Whereas the majority of the words in a text are fixated, sometimes even twice (i.e. refixation; 15% of total fixations), many words are skipped; 2–3 letter words, for instance, only receive a fixation about 25% of the time. On average, a fixation during reading lasts for about 200–250 ms and is followed by a saccade to some 7–9 characters forward (~2–3°). About 10–15% of our reading saccades are regressive. Towards the end of a line of text, a large right-to-left slightly oblique saccadic eye-movement is made close to the beginning of the next line. The size of the return-sweep depends upon line length (usually about 50 characters, ~17°) (Rayner, 1998; Rayner & Pollatsek, 1989). In continual information sampling, eye-movements may be coupled with head-movements. As most studies of reading eye-movements immobilize the head, relatively little is known about eye-head coordination and the role and pattern of head-movements in reading (Lee, 1999).

Eye-movements during reading are systematically influenced by visual and lexical characteristics of the text information extracted during a fixation (Rayner & Pollatsek, 1981). The region of effective processing during reading, the perceptual span, extends about 3–4 characters to the left and up to 15 characters to the right of fixation (in left-to-right writing systems). As one degree of visual angle encompasses about 3 characters for most normal text (Leff et al., 2000), these values are equivalent to ~1.3° to the left and 5° to the right of fixation (McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979). Visual acuity falls symmetrically to either side of

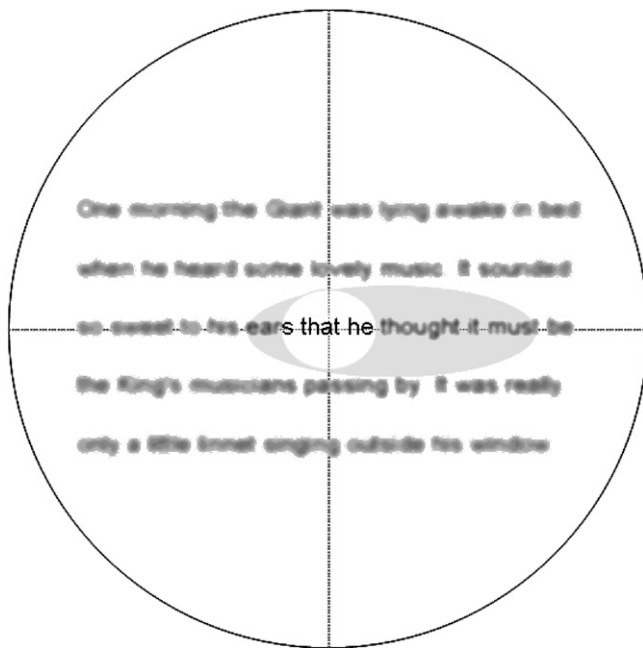


Fig. 1. Schematic illustration of the visual field and perceptual span for text processing in normal readers. During a fixation, readers extract visual information from the foveal visual field (central white oval) and the parafoveal visual field (grey ellipse). Note that the drawing is schematic and not drawn to scale; the cross-hairs indicating fixation position do not resemble the actual initial fixation position, which would be probably on the “h” of the fixated word “that” in normal readers (optimal viewing position).

foveal vision and the distribution of the perceptual span is therefore likely to reflect an attentional asymmetry in reading. Acuity limitations determine only its right boundary. Discriminating fine detail such as letters is only possible within the foveal region, which extends out 1° to either side of fixation. Visual acuity and processing speed decrease sharply with increasing eccentricity in the horizontal direction, and even more so in the vertical direction (Anstis, 1974). Therefore, readers are able to gain letter identity information up to 7–8 characters to the right of fixation (McConkie & Zola, 1987; Rayner, Well, Pollatsek, & Bertera, 1982; Underwood & McConkie, 1985). Beyond this, only coarse textual features can be discerned up to the rightward boundary of the parafoveal visual field (Rayner, 1998). The range of letters that can be reliably identified without moving the eyes, i.e. shifts of fixation, is called word identification span or visual span. This range depends, of course, on print size; larger fonts are more discriminable but, with increasing font size, letter strings will fall further into the visual periphery with a concomitant drop in acuity (Legge et al., 2007). The perceptual span for text processing, composed of the foveal and parafoveal visual field, is illustrated in Fig. 1. Since the perceptual span's spatial extent exceeds the average-sized word at a given fixation and the mean amplitude of reading saccades, text material is scanned in a highly overlapping manner (Ikeda & Saida, 1978; Rayner & Bertera, 1979).

Foveal processing of fixated words enables lexical access and hence word identification. Fixation duration is influenced by factors such as word frequency, predictability and age-of-acquisition (Rayner, 1998). During successive saccades, foveal processing is facilitated by information that has been extracted from the right parafovea on the preceding fixation, i.e. the so-called parafoveal preview benefit (Rayner, 1975; Rayner, White, Kambe, Miller, & Liversedge, 2003). Such information includes that of word-length, which is used for the selection of the to-be-fixated word and the specification of the saccadic amplitude (Ducrot & Pynte, 2002; Inhoff, Radach, Eiter, & Juhasz, 2003).

2.2. The neural basis of text reading

Our knowledge about the neural basis of reading continuous text is sparse compared with what is known about the neural mechanisms underlying single-word reading (for a recent review on word identification, see Jobard, Crivello, & Tzourio-Mazoyer, 2003). The neural mechanisms involved in text reading, which involves the initiation and maintenance of an oculomotor scanpath in addition to word identification, has been investigated in only two studies (Leff et al., 2000; Leff, Scott, Rothwell, & Wise, 2001). Reading involves visual, attentional, oculomotor and language processes (Rayner & Pollatsek, 1989), which are supported by large-scale neural networks (Mesulam, 1990). Distributed and coordinated processing relying on multiple cortical and subcortical brain regions suggests that white matter pathways connecting these regions play a crucial role (Ben-Shachar, Dougherty, & Wandell, 2007; Binder & Mohr, 1992).

Visual information is transmitted from the retinae to the primary visual (striate) cortex via the optic nerves, the optic chiasm, the optic tracts, the lateral geniculate nucleus, and the optic radiation (Grüsser & Landis, 1991). The striate cortex (V1), the prestriate visual area V2, the posterior parietal cortex and frontal eye fields, as well as the supplementary eye fields and the dorsolateral prefrontal cortex form a network which integrates vision, attention and eye-movements. Subcortical structures, particularly the superior colliculus and thalamus, also contribute to saccade control (for a more detailed discussion, see Leigh & Zee, 2006; Pierrot-Deseilligny, Rivaud, Gaymard, Müri, & Vermersch, 1995). This distributed neural system subserves the bottom-up (i.e. stimulus-driven) and top-down (i.e. goal-directed) control of visual-spatial attention and saccadic eye-movements via feedforward and feedback connections (Corbetta, 1998; Corbetta & Shulman, 2002). Although “attention and ocular control did not evolve for reading (...), reading is a special application of the attentional/ocular control system” (Kliegl & Engbert, 2003, p. 492).

The primary visual cortex (V1) appears indispensable for visually guided eye-movements and word identification during reading since it represents the foveal and parafoveal visual field (Leff, 2004). There is evidence that the eyes are disparate on 40–50% of fixations during reading (Kirkby et al., in press). It has therefore been suggested that a single perceptual representation is achieved through the visual integration of the two disparate retinal signals at a very early stage in the visual pathway (Liversedge, Rayner, White, Findlay, & McSorley, 2006). Word identification involves the activation of left and right striate and ventral prestriate cortex where foveal vision is represented. The guidance of reading eye-movements requires the representation of right parafoveal vision in the left primary visual cortex and neighbouring V2. The asymmetric activation of left parafoveal V1/V2 during text reading has been interpreted as physiological confirmation of the perceptual span's asymmetry, which is controlled by top-down attentional factors (Leff et al., 2000). This top-down attentional modulation of early visual information processing is mediated by fronto-parietal activity (Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; Russell, Malhotra, & Husain, 2004) and results in the directing of visual attention to the right of fixation during reading (Upton, Hodgson, Plant, Wise, & Leff, 2003). Attentional processes facilitate visual processing in the striate and extrastriate cortices (Martinez et al., 2001) and in the ventral occipito-temporal stream (Mangun, Hopfinger, Kussmaul, Flechter, & Heinze, 1997), which is crucially involved in high-resolution, local processing of visual features and object identification (Milner & Goodale, 2006). Thus, “attention during reading acts early in the visual hierarchy” (Leff et al., 2000).

As words can be regarded as visual objects, the ventral stream has been implicated in word processing and identification pro-

cesses (Poldrack, Desmond, Glover, & Gabrieli, 1998) which are associated with an activation of the foveal part of the left and right occipital cortex (V1/V2) (Brewer, Liu, Wade, & Wandell, 2005) and the left posterior occipito-temporal junction in the inferior temporal gyrus (Leff, Crewes, et al., 2001). Word identification is also the first stage of linguistic processing; its successful accomplishment provides the basis for intact language comprehension as it makes semantic, syntactic and thematic information available (Liversedge & Blythe, 2007). Left occipito-temporal activation might also be mediated by top-down influences from the left-lateralized major language-processing areas involved in reading (Powell et al., 2006), i.e. the posterior superior temporal gyri, implicated in lexical and semantic processing, and the inferior frontal cortex, implicated in syntactic processing (Binder et al., 1997).

The posterior parietal cortex (PPC) is crucial for the generation of a visuospatial representation (based on bottom-up visual input from the parafoveal visual field) which then can be used by prefrontal mechanisms to guide attention and eye-movements concerned with visual information sampling from the top-down, i.e. visuomotor integration (Andersen & Buneo, 2003; Zihl & Hebel, 1997). The projections from the parafoveal part of V1/V2 to posterior parietal regions illustrate the significance of the parafoveal visual field for the visual-spatial control of reading saccades. The transformations carried out in the dorsal processing stream mediate visuomotor control, and are thus an interface between perception and action (eye-movements) (Milner & Goodale, 2006). Bilateral activation of the PPC, with a greater signal on the left is associated with efficient reading saccades from left-to-right, i.e. into contralateral hemispace. Evidence suggests that it controls the online maintenance and modification of a sensorimotor plan which is required to read along each single line of text (Leff et al., 2000; Leff, Scott, et al., 2001).

Bilateral activation of the frontal eye fields (FEF), with a greater signal on the right is associated with the preparation of this sensorimotor plan at the beginning of each new line and with performing the return-sweep, which interrupts the oculomotor scanpath and requires a change of the sensorimotor plan (oculomotor flexibility). FEF activation is minimal for the continued generation of saccadic reading eye-movements along a line of text. The FEF seem to be less important for visually guided saccades but are crucial for intentional, voluntary generated saccades irrespective of their direction (Leff et al., 2000; Leff, Scott, et al., 2001). The FEF plays a key role in the top-down control of oculomotor scanpaths that follow a previously learned rule (e.g. reading direction imposed by the writing system). In addition, the oculomotor aspects of eye-movement control interact with cognitive processes underlying visual word identification, which may also determine how long attention maintained at a specific position, i.e. the temporal aspect of saccade programming (Heinzle, Hepp, & Martin, 2007). Higher-level linguistic processing activities in the left anterior inferior prefrontal and left temporo-parietal cortex may also influence the duration of a fixation from the top-down (Posner, Abdullaev, McCandliss, & Sereno, 1999).

3. Hemianopic dyslexia: reading when the visual world shrinks

Mauthner (1881) was the first to describe the effects of unilateral homonymous visual field defects on reading. His classic description marks the starting point of research into hemianopic dyslexia. Wilbrand (1907) termed this reading impairment associated with unilateral homonymous visual field loss “macular-hemianopic reading disorder” since hemianopia is the typical and most frequent

visual disorder after brain injury (see also Poppelreuter, 1917/1990). It is the “cardinal symptom” which dominates all postchiasmatic visual pathway pathologies (Lenz, 1909).

3.1. Introducing cerebral visual field disorders

Homonymous visual field disorders account for about 20% of functional impairments after brain damage (Zihl, 2000, 2003). They are caused by injury to the postchiasmatic visual pathway, i.e. to the optic tract, the lateral geniculate nucleus, the optic radiation, or to the primary visual cortex (located at the calcarine sulcus) (Zhang, Kedar, Lynn, Newman, & Biouesse, 2006). For these patients the “visual world shrinks” as vision is lost in both monocular hemifields contralateral to the side of brain injury (Grüsser & Landis, 1991, p. 136). Sufficient spontaneous recovery of the visual field occurs rarely and, therefore, homonymous visual field deficits can be regarded as chronic manifestations (Zihl & Kennard, 1996).

In addition, posterior cerebral artery infarctions, the most common aetiology underlying homonymous visual field loss (~70%, see Zhang et al., 2006; Zihl, 2000), are seldom restricted to calcarine cortex only. Additional lesions to the occipital white matter, which might affect fibre pathways connecting occipital, parietal, temporal and frontal cortical regions, as well as to the posterior thalamus are the rule rather than the exception for these patients (Hebel & von Cramon, 1987). As a consequence, the majority of patients (about 70%) show persistent and severe impairments of reading and visual exploration (for oculomotor scanning in hemianopia, see Pambakian et al., 2000; Tant, Cornelissen, Kooijman, & Brouwer, 2002; Zihl, 1995b, 1999, 2000).

Visual field disorders can be measured quantitatively by perimetric techniques (see, e.g., Aulhorn & Harms, 1972) and are classified according to the portion of the visual field affected. After unilateral damage, the most common type is hemianopia, the loss of vision in one hemifield (of both eyes), followed by quadrantanopia, the loss of vision in one quadrant, and paracentral scotoma, a small island-like field defect in the parafoveal visual field. Left-sided lesions result in right-sided visual field defects, and *vice versa*. After bilateral brain injury, corresponding portions in both visual hemifields are affected. The resulting disorders are analogously termed: bilateral hemianopia (tunnel vision), bilateral upper or lower quadrantanopia, and bilateral paracentral scotoma. The loss of vision in the central visual field region is referred to as central scotoma. Unilateral visual field disorders are much more common than those resulting from bilateral brain injury (~90% of patients with visual field disorders) (Zihl, 2000). Depending on the quality of the deficit, vision can either be completely lost (anopia) or one or more visual functions in the affected visual field can be reduced (amblyopia). In cerebral amblyopia, light sensitivity is reduced whereas form and/or colour vision is lost. The selective loss of colour vision is referred to as achromatopsia (Heywood & Kentridge, 2003). Testing visual functions like colour and form vision requires the use of special targets and procedures in perimetric testing (see Aulhorn & Harms, 1972).

The extent of visual field sparing in the affected hemifield is measured in degrees of visual angle from the fovea. In unilateral postchiasmatic damage, the foveal or central visual field (± 0.5 – 1.0°) is always spared. Macular sparing (visual sparing between 1 and 5° to the left or right of fixation) is seldom and most likely results from incomplete damage to the striate cortex or its afferent connections (Zihl, 1989; Zihl & von Cramon, 1986). Approximately 75% of patients with unilateral homonymous visual field disorders present a parafoveal visual field sparing of less than 4° . Visual field sparing (co-)determines the resulting functional visual impairment. As a rule, patients with a smaller field sparing are more disabled, especially with regard to visual functions that crucially depend on

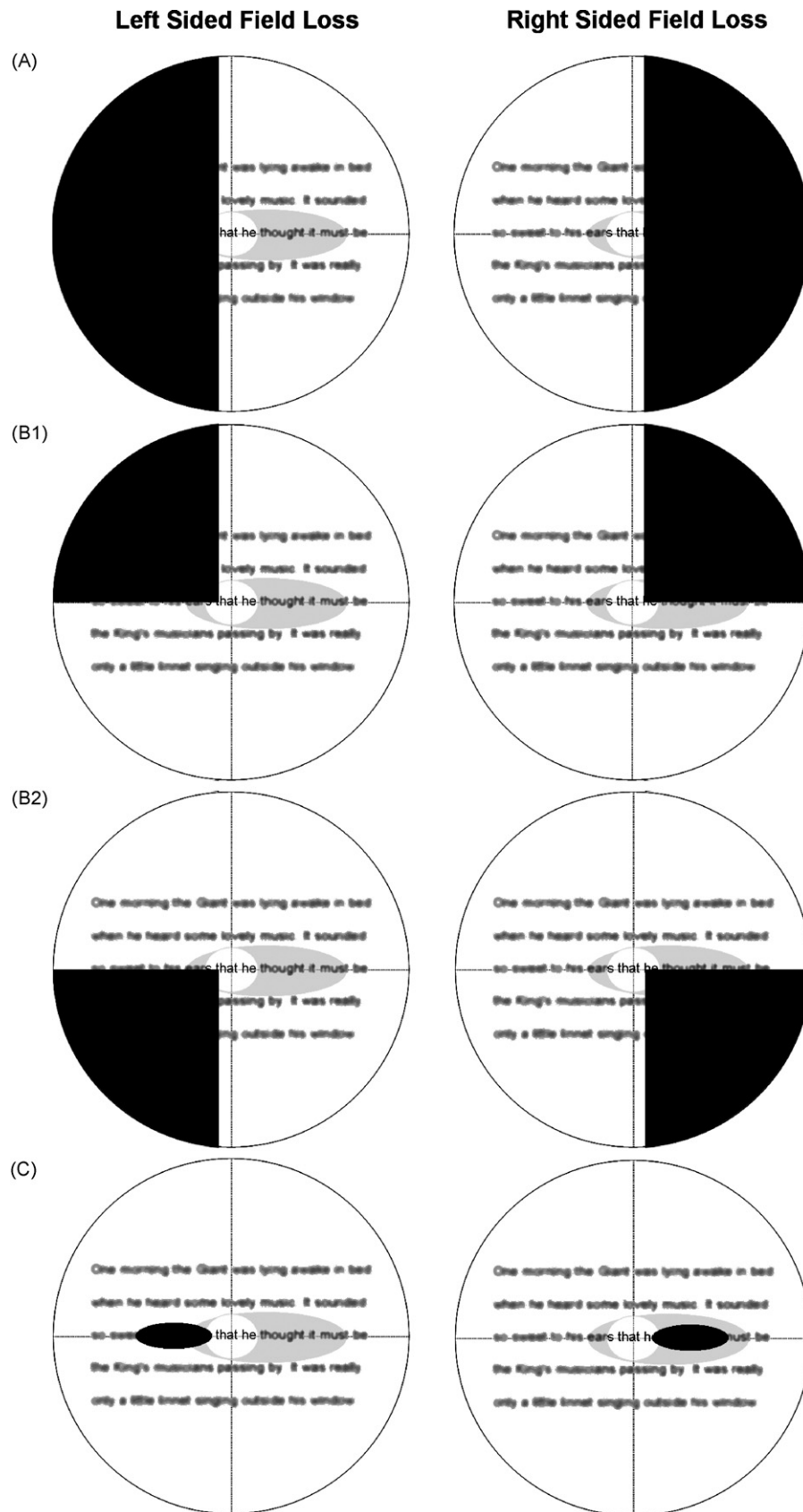


Fig. 2. Schematic illustration of the visual field and perceptual span (comprising of foveal (central white oval) and parafoveal vision (grey ellipse)) for text processing in patients with left- or right-sided unilateral homonymous parafoveal visual field loss (field sparing: $\sim 1^\circ$) (affected binocular regions in black). (A) Hemianopia; (B1) upper quadrantanopia; (B2) lower quadrantanopia; (C) paracentral scotoma. Note that the drawing is schematic and not drawn to scale. The cross-hairs indicating fixation position do not resemble the actual initial fixation position, which would be probably located to the left of the optimal viewing position (i.e. left of the “h” in “that”) in right-sided field loss (McDonald et al., 2006; Spitzyna et al., 2007); for left-sided field loss, the initial fixation position has not yet been investigated.

the parafoveal region, such as reading (Zihl, 1989, 2000). When parafoveal visual field sparing is smaller than 4°, 75% of patients with left-sided field loss and as many as 92% of patients with right-sided defects show pronounced reading difficulties, i.e. hemianopic dyslexia (Zihl, 1994). Fig. 2 schematically illustrates the visual field and perceptual span for text processing in left- or right-sided hemianopia, quadrantanopia, and paracentral scotoma. When visual field sparing ranges between 5° and 10°, reading is still yet less disturbed in about 25% of cases. Reading is rarely impaired when field sparing exceeds 10° (Zihl, 2000).

Diagnosing hemianopic dyslexia requires the presence of a homonymous unilateral parafoveal visual field loss (as confirmed by detailed perimetric testing). It is essential to exclude disorders of visual acuity, spatial contrast sensitivity, visual adaptation, disturbances of the anterior visual pathways or the oculomotor system, macular disease (as revealed by ophthalmological examination) and language disorders that could interfere with the correct processing of text material. Wilbrand (1907) clearly differentiated hemianopic dyslexia from aphasic reading disorders. In hemianopic dyslexia, reading is impaired despite intact lexical and post-lexical processes (see also Best, 1917; Poppelreuter, 1917/1990).

A hemianopic reading impairment also must be clearly distinguished from pure alexia (letter-by-letter reading) (for the first report, see Dejerine, 1891). Although pure alexia is usually accompanied by a right-sided hemianopia, the visual field defect is not causally linked to it (for a collection of key articles, see Coltheart, 1998). Pure alexia seems to be associated with a serial encoding of letters (Behrmann et al., 2001; Rayner & Johnson, 2005). The diagnosis of hemianopic dyslexia also requires the absence of any signs of visual-spatial neglect in standard tests. Left-sided hemianopia and visual-spatial neglect often coexist and can be difficult to disentangle (Walker, Findlay, Young, & Welch, 1991). Despite the absence of neglect symptoms, however, patients may nevertheless exhibit neglect dyslexia (for the first report, see Brain, 1941). Evidence suggests a clear double dissociation between neglect symptoms and neglect dyslexia (for a review, see Haywood & Coltheart, 2000; Riddoch, 1991). Recently, neglect dyslexia was interpreted as a deficit of extracting visual information from the left side of space (Behrmann, Black, McKeeff, & Barton, 2002). Explaining neglect dyslexia in this manner may be reminiscent of hemianopic dyslexia. Yet, both reading impairments are distinct disorders and have to be differentiated.

3.2. Reading performance and eye-movements in hemianopic dyslexia

Since Mauthner's (1881) first description, several studies have dealt with hemianopic dyslexia and a high degree of consensus about its characteristics has been reached. It has consistently been shown that a visual field defect "is a disturbing obstacle and, depending on its location to the right or left of the fixation position, unpleasantly manifests itself in different ways" (Wilbrand, 1907, p. 6, our translation). Yet, not only whether right- or left-sided parafoveal vision is affected but also how much of it is spared (co-)determines type and severity of the resulting reading impairment in homonymous visual field disorders (Mackensen, 1962). It is noteworthy that most findings are based on investigations of left-to-right text reading in patients with unilateral left- or right-sided unilateral homonymous hemianopia (LH, RH).

3.2.1. Reading performance

In hemianopic dyslexia research reading speed (correctly read words per minute, wpm) and accuracy (uncorrected reading errors), the standard measures of reading performance, are recorded while patients engage in reading aloud standardised texts, as quickly and

Table 1

Examples of oral reading in patients with left-sided (A) or right-sided (B) unilateral homonymous parafoveal visual field loss (field sparing: ~2°) ([a]b) indicates visual omission errors; [pause] indicates reading interruptions; guessing errors are italicised)

| | |
|--|--|
| Original text | |
| The trees were in leaf, and the rumps of the tourist buses were thick and fat in the traffic, and all the farmers wanted fertilizer admixes rather than storehouse insulation when Sixsmith finally made his call. In the interim, Alistair had convinced himself of the following: before returning his aggrieved letter, Sixsmith had steamed it open and then resealed it. During this period also, Alistair had grimly got engaged to Hazel. But the call came | |
| (A) | [The] trees were in leaf, and [the] rumps of the tourist [b]uses [pause] buses were thick and fat [in] the traffic, and all the [pause] farmers wanted fertilizer [ad]mixes rather than [store]house insulation when [Six]smith finally made his call. In the interim, Alistair had convinced [him]self [pause] himself of the following: before [re]turning his [ag]grieved [pause] aggrieved letter, [Six]smith had steamed it open and then [re]sealed [pause] [re]sealed it. During this period also, Alistair had grimly got [en]gaged [pause] engaged to Hazel. But the call came |
| (B) | The trees were in [leaf], and the rumps of [the] tourist buses were thick and fat [in] the traffic, and all [the] farmers want[ed] fertile [pause] wanted to be fertile [pause] admix[es] [pause] admixture [pause] rather than store[house] [pause] insulation when Six[smith] [pause] finally made his call. In the interim, Ali[stair] [pause] Alistair had convince[d] to convince[d] [pause] himself of the following: before return[ing] the return[ing] of his aggrieved letter, Six[smith] had steamed it open and then resealed it. During this period also, Ali[stair] had grimly got engage[d] to Hazel [pause] an engagement with Hazel. But the call came |

Note. The text is taken from Amis (1994). Figure is adapted from Zihl (2000, p. 72).

accurately as possible. These texts are easy to comprehend and letter size, spacing between lines, words and letters are maintained as optimal for reading. Reading speed is significantly reduced in both LH and RH, in comparison with age-matched normal readers. Slowness of reading is the distinctive attribute of hemianopic dyslexia, and applies not only to text but also to reading single words (Kerkhoff et al., 1992; Spitzyna et al., 2007; Zihl, 1995a, 2000; Zihl et al., 1984; Zihl & von Cramon, 1986). Reading time increases with each additional letter, especially in patients with small visual field sparing. Yet the effect is not as pronounced as in letter-by-letter reading (Behrmann et al., 2001; Leff, Crewes, et al., 2001; Rayner & Johnson, 2005).

Patients make only relatively few reading errors and are, therefore, often overlooked in neuropsychological examinations. Nevertheless, reading errors in hemianopic dyslexia do occur and can be characterised as visual omissions of letters, syllables, and even short words. Patients also make meaningful completions of only partially seen words by adding syllables to their beginning or to their end. As a result, errors are introduced by guesses. Patients do not show letter-by-letter reading or spelling errors. Reading errors are caused by the visual field defect at the visual-sensory level. They are visually related to the actual word being read and consistently affect just one side of the word, i.e. the side of the blind field (Zihl, 1995a, 2000). Examples of oral reading in patients with hemianopic dyslexia are presented in Table 1.

Oral reading performance (reading speed and errors) considerably differs between left- and right-sided parafoveal visual field defects. Patients with a left-sided defect require about twice as much reading time as normal readers. An average reading speed of 78 wpm was measured in a sample of left-sided hemianopic patients whereas the corresponding figure for normal subjects (N) was 174 wpm (Zihl, 2000). Reading errors mainly consisted of omissions of prefixes and small words, especially at the beginning of lines (~4 errors, Zihl, 1995a) (see Table 1(A)). In patients with a right-sided defect reading speed was only ~56 wpm (Zihl,

2000). They also made three times as many errors as patients with left-sided field loss (~13 errors, Zihl, 1995a). These errors can be characterised as omissions and substitutions of suffixes and small words, especially at the end of lines (see Table 1(B)).

The reading impairment as defined by reading rate and number of errors is not only related to the side but also to the severity of the parafoveal visual field loss. Reading time and errors increase with decreasing visual field sparing. This inverse relationship holds for both left- and right-sided parafoveal visual field loss but is more pronounced in right-sided field loss (LH: <3°: 53 wpm, >5°: 124 wpm; RH: <3°: 43 wpm, >5°: 98 wpm) (Zihl, 2000).

3.2.2. Reading eye-movements

The first formal electro-oculographic investigations of hemianopic dyslexia were carried by Remond, Lesevre, and Gabersek (1957) (cited in Ciuffreda, 1994), followed by Mackensen (1962) and Gassel and Williams (1963a). Mackensen (1962) viewed reading as a sensorimotor ability and therefore regarded the study of eye-movements in hemianopic dyslexia as indispensable. His eye-movement recordings revealed a dramatic increase in the number of fixations and saccades. Gassel and Williams (1963a) observed similar irregularities in a larger sample of patients with unilateral homonymous hemianopia. The severe alteration of the oculomotor reading pattern is the most objective behavioural manifestation of the reading impairment in hemianopic dyslexia.

Detailed eye-movement analyses have provided a comprehensive understanding of the global temporal and spatial oculomotor measures associated with text processing during silent reading in hemianopic dyslexia (Zihl, 1995a, 2000). Overall, prolonged fixation durations (LH: 310 ms; RH: 410 ms; N: 250 ms), smaller amplitudes (LH: 4.0°; RH: 3.2°; N: 4.3°), more fixations (LH: 76; RH: 87; N: 56), and a much higher percentage of refixations (LH: 37%; RH: 44%; N: 15%) have been reported (Zihl, 2000). The increased number and duration of fixations and especially the increased likelihood to refixate words seem to account for the slowness of reading in hemianopic dyslexia (McDonald et al., 2006; Zihl, 1995a).

Although word-based analyses of text reading are standard in experimental reading research (Rayner, 1998), it is only recently that local spatial and temporal oculomotor measures have been obtained in patients with right-sided hemianopia. The initial landing position for longer words moves from the centre towards the beginning and small words are less likely to be skipped (RH: 22%; N: 63% (3-letter-words)). First fixation and gaze durations as well as the total fixation time are about twice as long as in normal readers (McDonald et al., 2006; see also Spitzyna et al., 2007). Like experimental reading research all hemianopic dyslexia research has been based on monocular eye-movement recordings. Binocular recordings of eye-movements in hemianopic dyslexia may provide further insights into the binocular coordination of reading eye-movements and the mechanisms underlying the formation of a single perceptual representation from disparate retinal signals (Liversedge et al., 2006).

The differential effects of left- and right-sided parafoveal visual field loss on reading eye-movement patterns were reported by Mauthner (1881). Patients with left-sided hemianopia showed difficulties to find the beginning of a new line. When compared to the impairments associated with right-sided hemianopia, Mauthner regarded these difficulties as negligible. In left-sided hemianopia, to him the “more pleasant” disorder, “only the words which have already been read disappear, and looking ahead at the upcoming words is not disturbed” (p. 370, our translation) whereas in right-sided hemianopia “the despair is enormous that from the point of fixation the visual field is cut off completely in the direction of reading; hence nothing can be read ahead” (Mauthner, 1881, p. 370, our translation). Wilbrand (1907) described a considerable uncertainty

and hesitation about where to move the eyes next in patients with right-sided parafoveal visual field loss; to him, it looked as if their eyes were stuck at the currently fixated word (see also Best, 1917).

The differences between left- and right-sided parafoveal visual field loss in the majority of global eye-movement parameters are illustrated in Fig. 3. In left-sided field visual field loss, the oculomotor reading pattern differs from the typical staircase pattern of normal readers (see Fig. 3(A)) although overall reading performance can be regarded as slowed yet, more or less, fluent reading. The return-sweep appears fragmented. It is reduced to half of its normal size (LH: 9.4°; N: 17.3°) (Zihl, 1995a) and is broken down into many small saccades (Mackensen, 1962). Patients make many more smaller leftward saccades and show a higher percentage of repetitions of saccades and fixations to the left (Zihl, 2000) (see Fig. 3(B)). A right-sided visual field defect, on the contrary, impairs shifting the gaze systematically from left-to-right while the return-sweep remains unaffected. The staircase-like oculomotor reading pattern is severely deteriorated and replaced by many small and irregular saccadic eye-movements to the right (see Fig. 3(C): ellipse). The amplitude of rightward saccades is significantly reduced and the total number of saccades increases (Zihl, 2000). Numerous leftward-directed regressions occur (see Fig. 3(C): small arrow) and fixation durations are considerably prolonged (up to 1.5 s, Zihl, 1995a) (see Fig. 3(C): ovals). These findings have been confirmed and replicated elsewhere (De Luca et al., 1996; Eber, Metz-Lutz, Bataillard, & Collard, 1987; Leff et al., 2000; McDonald et al., 2006; Schoepf & Zangemeister, 1993; Spitzyna et al., 2007; Trauzettel-Klosinski & Brendler, 1998).

The degree of visual field sparing also clearly contributes to the irregularities of the oculomotor pattern in terms of an inverse relationship. Patients with only 1–2° of field sparing show the most disturbed oculomotor reading pattern, in particular when the right hemifield is affected. Patients with a right-sided defect and 5° of sparing are still much more disabled than patients with a left-sided defect of the same extent who show a close to normal reading eye-movement pattern (Fig. 4) (De Luca et al., 1996; Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995a, 2000).

If at least 3° to the left and 5° to the right of fixation are spared in homonymous visual field loss, reading is nearly unimpaired (Mackensen, 1962; Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995a, 2000). Yet, how much visual field sparing is required for reading to be unimpaired might be better described in number-of-characters than in degrees-of-visual-angle. It is the number of characters (in relation to print size) that determines saccade size in reading (Morrison & Rayner, 1981; O'Regan, 1983) and sets the spatial boundary of the perceptual and word identification span. Describing visual sparing in terms of number of characters rather than visual angle may also explain better Wilbrand's (1907) finding that the reading impairment of his patients with a paracentral scotoma was more pronounced for small print, despite normal visual acuity. Print size determines the number of letters which can be identified at a glance; the smaller the print, the smaller is the word identification span (Anstis, 1974). The values given above as critical visual field requirement for unimpaired reading in patients with visual field defects hold for text that has 3 characters per degree. Thus, according to hemianopic dyslexia research the perceptual span extends 15 characters to the right and 9 to the left of fixation, confirming the asymmetry as well as the right boundary of the perceptual span in normal readers (McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979).

The left boundary may vary depending on whether readers engage with a text passage or with a single sentence. Only in the former case return-sweeps have to be performed, which may require 9 rather than 3–4 characters to the left of fixation. One may speculate that the perceptual span flexibly adapts to the changed reading

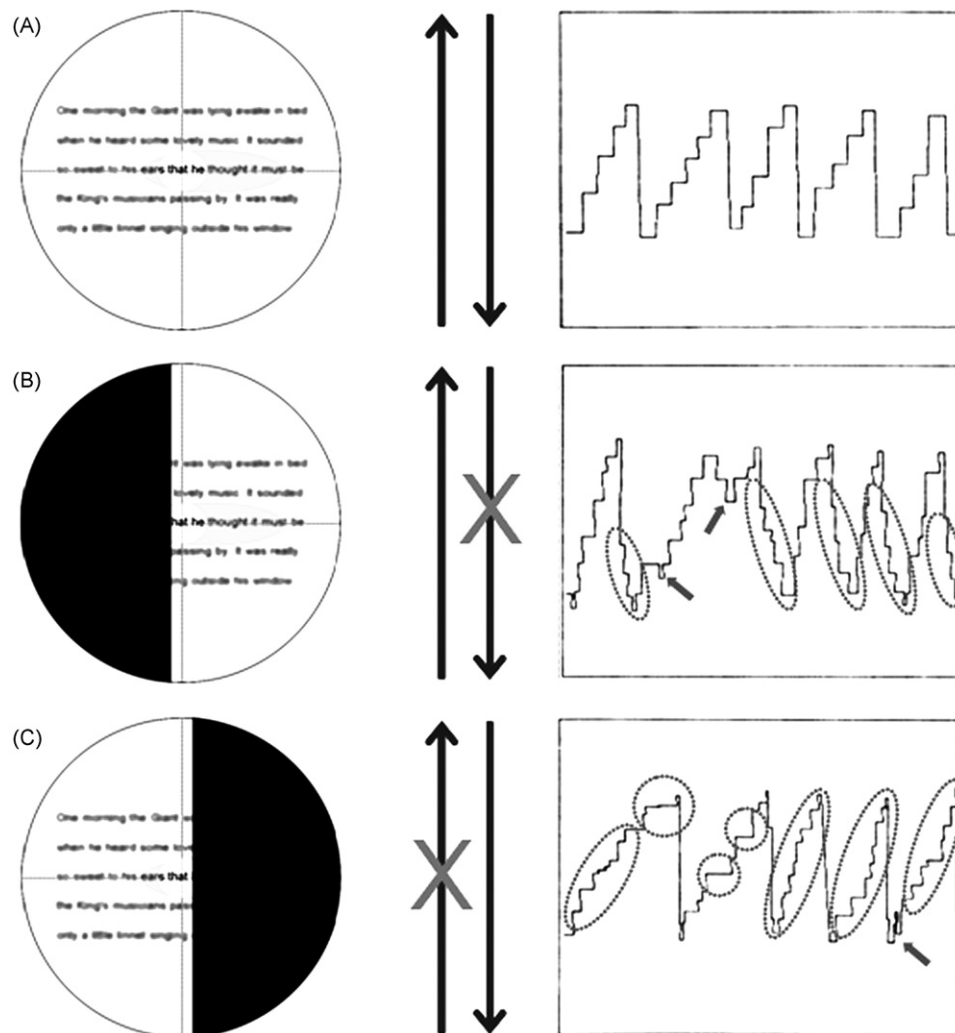


Fig. 3. Infra-red eye-movement recordings in normal readers (A) and in patients with left- (B) or right-sided (C) unilateral homonymous hemianopia (field sparing: $\sim 1^\circ$). For illustration purposes, eye-movement patterns for reading five lines (x-axis: time period of recording; y-axis: horizontal extension of line from left to right) are shown in relation to the visual field and perceptual span for text processing (B and C: affected binocular regions in black). Downward arrows indicate moving the eyes from the end to the beginning of a new line (which is disturbed in B (crossed arrow) as indicated by ellipses); upward arrows indicate moving the eyes from the beginning to the end of a line (which is disturbed in C (crossed arrow) as indicated by ellipses). Ovals indicate prolonged fixations, small arrows indicate regressions. Eye-movement recordings are adapted from Zihl (1995a).

direction (right-to-left) and becomes asymmetric to the left of fixation. This would also explain the finding that the first word is often not fixated in normal reading (Rayner & Pollatsek, 1989) and usually omitted in left-sided parafoveal visual field loss (Wilbrand, 1907).

Most studies investigated reading in patients with hemianopia and, therefore, less is known about the distinctive effects of a quadranopia or paracentral scotoma (see Fig. 2: B1/2, C). Nevertheless, there are some data available suggesting that the

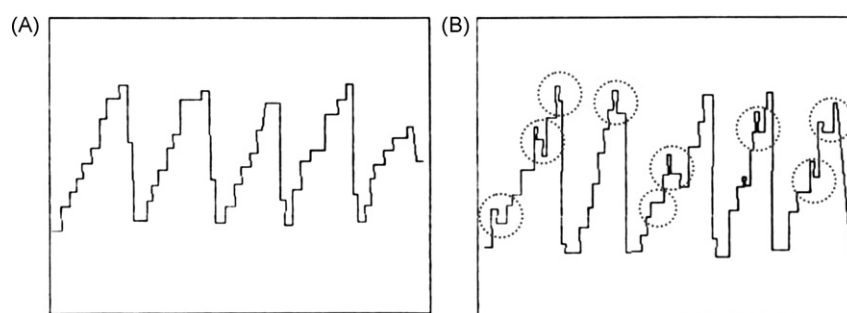


Fig. 4. Infra-red eye-movement recordings in patients with left- (A) or right-sided (B) unilateral homonymous hemianopia (field sparing: $\sim 5^\circ$). Eye-movement patterns during reading of five lines are shown (x-axis: time period of recording; y-axis: horizontal extension of line from left to right). Note the more or less regular oculomotor reading pattern in A in comparison to the distorted oculomotor pattern in B (ovals indicate regressions and prolonged fixations). Eye-movement recordings are adapted from Zihl (1995a).

characteristic reading difficulties are present in all patients with unilateral homonymous visual field disorders if parafoveal vision is affected by brain injury (Mackensen, 1962; Wilbrand, 1907; Zihl, 2000). Although seemingly small and negligible, paracentral scotomata can disturb reading substantially: Wilbrand's (1907) patients reported a "notorious impediment to their usual speed when gliding along the lines of text" (p. 1, our translation) (see also Mackensen, 1962). Yet investigations of single cases suggest that reading speed is higher and the number of fixations and refixations much smaller than in patients with a hemianopia. A quadrantanopia seems to affect reading performance and oculomotor parameters even less than paracentral scotoma (Zihl, 2000).

Furthermore, it seems that no complete loss of vision (anopia) is necessary for a reading impairment to emerge. Amblyopic forms of unilateral homonymous visual field disorders can cause hemianopic dyslexia if the residual visual field for form vision is smaller than 4–5°. Since text processing requires the visual discrimination of forms (letters), the reading impairment in homonymous hemi-amblyopia is almost identical with the impairment in hemi-anopia (Wilbrand, 1907; Zihl, 2000). Hemianopic dyslexia is quite common in homonymous hemi-amblyopia as only 25% of these patients show at least 5° of visual sparing (Zihl, 1994). Only recently a case of subtle hemianopic dyslexia in right-sided unilateral homonymous quadrant-amblyopia has been reported in detail. The threshold for luminance detection was elevated and form vision (especially for letters) was severely reduced in the upper right quadrant. Text reading was slowed down and the number of reading errors significantly increased. Minor abnormalities in the oculomotor reading pattern were found (Habekost & Starrfelt, 2006).

4. Reading without a parafovea: seeing only half the wor(l)d

Despite a growing literature on reading impairments in unilateral homonymous visual field defects and relatively consistent results, the explanation of hemianopic dyslexia is still in its infancy. Mauthner (1881) and Wilbrand (1907) suggested that it is the loss of the parafoveal visual field in unilateral homonymous visual field disorders which causes hemianopic dyslexia. The discussion of the effects of parafoveal visual field loss on word identification and oculomotor control in reading, both at the behavioural and neural level, demonstrates the significance of parafoveal vision for reading. Yet, we have to keep Poppelreuter's (1917/1990) remark in mind that explaining hemianopic dyslexia as merely a functional consequence of parafoveal visual field loss may not provide the full story.

4.1. Word identification without a parafovea

The activation of the left occipito-temporal junction associated with word identification processes is still present in patients with right-sided homonymous hemianopia. Even patients with a very small visual sparing show this activation although the necessary input from left striate cortex representing right foveal and parafoveal vision is missing (Leff, Crewes, et al., 2001). In contrast to pure alexia, the left occipito-temporal junction as well as its afferents from left and right striate cortex is spared in hemianopic dyslexia (Leff et al., 2006). Hence, information from the intact contralateral (i.e. right) striate cortex (representing the left visual field) must be transferred to the left occipito-temporal junction via the splenium of the corpus callosum. Intact afferent connections from the right occipital cortex to the left occipito-temporal junction appear sufficient to support word identification in patients whose right parafoveal vision is compromised (Leff, Crewes, et al., 2001).

Word identification through this indirect route, however, can be regarded as less efficient. In left-to-right readers, words are processed and identified best in the right foveal/parafoveal visual field represented in the left striate cortex (Brysbaert & Nazir, 2005; Nazir, 2000; Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004). This may also explain the finding that patients with larger right-sided visual field sparing and patients with left-sided visual field loss (i.e. right-sided injury) are less impaired in word identification (Upton et al., 2003).

In most patients with unilateral homonymous parafoveal visual field loss the perceptual and visual span may be no more than 3–4 characters. Yet the more letters can be identified at a single fixation, the larger is the amplitude of reading saccades, which facilitates faster reading. The visual span imposes a limit on reading speed and is also referred to as the "sensory bottleneck" in reading (Legge et al., 2007). If this bottleneck is additionally restricted by parafoveal visual field loss, forward saccades become smaller and many more saccades have to be made to extract the same amount of text information for correct word identification. This effect is most pronounced when reading longer words (Leff, Crewes, et al., 2001; McDonald et al., 2006). Converging evidence stems from low vision readers whose visual and perceptual span is restricted by foveal processing difficulties due to macular disease (Chung, Legge, & Cheung, 2004; Crossland & Rubin, 2006; Legge, Ahn, Klitz, & Luebker, 1997).

Parafoveal visual field loss prevents that the beginning and end of a word are simultaneously visually apprehended. Especially longer words are never seen as a whole and parallel letter processing, which is required for efficient lexical word identification (Rayner & Pollatsek, 1989), is disturbed. Incomplete visual percepts of half-seen words are encoded and forwarded to higher-level linguistic processing units. Often, the visual input is insufficient to activate corresponding representations in the mental lexicon. If an incompletely encoded word makes sense and activates a lexical representation, visual omission errors emerge. Guessing errors occur if the predictive value of the incomplete percept is used for a meaningful completion of the word (Zihl, 2000). For instance, words which can be misread by omission or substitution of the first letter (e.g. peach: each or beach) increase the likelihood of errors in left-sided parafoveal visual field loss (Ellis, Flude, & Young, 1987).

Patients seem to over-rely on higher-level linguistic processes to compensate for the missing visual information when trying to identify words. Extracting meaning from an incompletely perceived word (comprehension) rather than inspecting the entire word first (visual apprehension) is the preferred strategy. Higher-level linguistic processes come into play too early which disrupts further acquisition and processing of text information located in the blind hemifield. Overall, processing words when the parafoveal visual field is compromised requires more time. Difficulties in word identification, which also affect language comprehension, are reflected by longer fixation durations. As regressions occur as attempts to correct linguistic processing difficulties (Rayner & Pollatsek, 1989), their increased number in parafoveal visual field loss is not surprising.

Hence, for processing text information, patients make use of their residual foveal/parafoveal vision and linguistic processes. Reading in parafoveal visual field loss can, therefore, still be regarded as non-random visual information sampling (see also McDonald et al., 2006). Further evidence stems from a small sample of patients with a left- or right-sided homonymous hemianopia (De Luca et al., 1996). Patients identified high-frequency words much quicker than low-frequency words. Reading passages containing low-frequency words was associated with an increased number of saccades and regressions, longer fixation durations and smaller saccadic amplitudes. Words embedded in a textual con-

text were identified quicker than words in isolation (contextual constraints). Meaningful words were inspected and read quicker than non-words (lexical constraints) (De Luca et al., 1996). Similarly, reading multi-digit numbers is much more prone to visual omission errors than is reading meaningful text material as much less facilitating top-down information becomes available (Zihl, 2000). One of Poppelreuter's (1917/1990) patients with a right-sided paracentral scotoma showed a pronounced reading impairment when confronted with meaningless or Latin text but "read familiar text (...) like a normal" (p. 224). High contextual constraint (as determined by word predictability) facilitates word skipping, reduces fixation durations and refixations (Binder, Pollatsek, & Rayner, 1999; Ehrlich & Rayner, 1981; Pynte & Kennedy, 2006; Rayner, 1998; Rayner & Well, 1996).

Right-sided parafoveal visual field loss affects not only processing the foveal word but also impairs preprocessing of the to-be-identified word located in the parafovea. During a fixation, readers process information from the fovea and parafovea; attentional top-down processes facilitate processing of the foveal text information first and the attentional focus then shifts to the parafoveal visual field (Reichle, Rayner, & Pollatsek, 2003). Parafoveal preprocessing is indispensable for maintaining fast and fluent reading (Blanchard, Pollatsek, & Rayner, 1989; Inhoff, 1987; Rayner, 1979; Rayner et al., 1982, 2003). The missing parafoveal preview benefit in right-sided parafoveal visual field loss contributes to the decreased likelihood of word skipping as well as to the overall increase in fixation duration and number of fixations (McDonald et al., 2006). Multiple words are no longer able to be processed during a single fixation and, therefore, a larger proportion of words have to be fixated. Furthermore, guiding reading saccades towards the centre of the to-be-fixated word where word processing is optimal (O'Regan & Lévy-Schoen, 1987; Vitu, O'Regan, & Mittau, 1990) becomes increasingly difficult as it requires right parafoveal word-length information. The initial fixation position wanders towards the beginning of the word and thus further away from the optimal viewing location. The resulting difficulties in word processing are reflected by longer fixation durations and an increased number of refixations (McDonald et al., 2006).

4.2. Visual guidance of reading eye-movements without a parafovea

Parafoveal visual field loss disturbs the integration of visual and motor process: "Successive gaze-shifts from left to right (...) are no longer in the order dictated by the visual information, but occur irregularly" (Poppelreuter, 1917/1990, p. 224). Visual information extraction from the parafoveal (and peripheral) visual field regions that provides the basis for a top-down control of visual attention and eye-movements in space and further local processing of fine details is impaired (Hochstein & Ahissar, 2002; Juan & Walsh, 2003; Upton et al., 2003). Word- and line-length as well as page boundary information may be represented at higher levels and form a coordinate system containing the relative spatial location of word-objects (Kennedy, Brooks, Flynn, & Prophet, 2003). This spatial coordinate system enables the attentional selection of the to-be-identified word. Saccades are computed accordingly and identification processes via local information processing of fine detail are initiated (Deubel, O'Regan, & Radach, 2000; Deubel & Schneider, 1996; McConkie & Zola, 1987).

Mackensen's (1962) observation that a paracentral scotoma produces a less pronounced reading impairment than a hemianopia may confirm such an assumption. He speculated that the lines above and below the paracentral scotoma may be used for visual guidance of reading eye-movements. A hemianopia, on the contrary, prevents the extraction of this visual information (compare

Fig. 2: A vs. C). Although the information below and above the current line does not affect oculomotor control in normal readers (Pollatsek, Raney, LaGasse, & Rayner, 1993), it may alleviate the reading impairment in patients with a paracentral scotoma.

A functional neuroimaging study (PET) investigated reading eye-movements in three patients with right-sided homonymous hemianopia and complete loss of right parafoveal vision (Leff et al., 2000). Eye-movement recordings of text reading revealed abnormal oculomotor reading parameters and reading speed was severely reduced. Instead of the left-lateralised PPC and right-lateralised FEF activation observed in normal readers, PPC was symmetrically activated and FEF activation was left-lateralised. Interestingly, a patient with a right-sided homonymous hemianopia that spared parafoveal vision showed the normal patterns of activation. His reading speed was in the range of age-matched controls and the oculomotor reading pattern was, despite a slight increase in the number of rightward saccades, more or less normal. Hence, the extent of the visual field defect seems to determine the level of functioning of the neural systems (PPC, FEF) subserving eye-movement control during text reading. Based on these results hemianopic dyslexia was interpreted as a disconnection of the motor systems involved in planning and guiding reading saccades from the representation of right parafoveal vision in the left striate and prestriate cortex (Leff et al., 2000).

In left-to-right reading, the left hemisphere (left striate and prestriate cortex, left-lateralised PPC activation) seems to be of greater importance for controlling oculomotor activities along a line of text than the right hemisphere (Leff et al., 2000; Leff, Scott, et al., 2001). The observation that right-sided parafoveal visual field loss (left-sided injury) impairs left-to-right reading more severely than a left-sided field loss (right-sided injury) is in line with this finding. However, one might question a fundamental, hard-wired asymmetry in cortical activities associated with text reading. Reading-related brain activation and its lateralisation appears to be functionally determined as indicated by investigations of the neural basis of reading across writing systems (Al-Hamouri et al., 2005; Bolger, Perfetti, & Schneider, 2005; Skoyles, 1988). Evidence suggests that cultural differences in writing systems are reflected by differential activation across the neural network(s) mediating reading-related processes (Schlaggar & McCandliss, 2007). The influence of reading direction on text information processing and related eye-movements might be mediated by a top-down control which determines the dynamics of visuospatial attention allocation, i.e. the size and location of the perceptual span (Osaka, 2003). The reversed asymmetry of the perceptual span in right-to-left writing systems such as Hebrew (Pollatsek, Bolozky, Well, & Rayner, 1981) supports this assumption.

Converging evidence stems from a case study that reports a skilled bilingual reader with a left-sided hemianopia who had pronounced reading difficulties in his mother tongue Hebrew (right-to-left reading) but not in his second language English (left-to-right reading) (Leker & Biran, 1999; Mohamed, Elsherbiny, & Goulding, 2000). That the asymmetry of the perceptual span in bilinguals flexibly adapts according to the reading direction of the language which is currently being read is in line with this study (Pollatsek et al., 1981). Already Mauthner (1881) speculated that the differences in reading impairment between left- and right-sided parafoveal visual field loss might be functional: in right-to-left writing systems a "right-sided hemianopia appears to be more desirable" (Mauthner, 1881, p. 370, our translation). Functional neuroimaging (and behavioural) studies of hemianopic dyslexia in right-to-left writing systems would be very illuminating in this regard. Comparing patients with right-sided parafoveal visual field loss in left-to-right writing systems with patients showing left-sided parafoveal visual field loss in right-to-left writing systems

might clarify the (relative) significance of left-lateralized activation of the cortical structures involved in text processing and related eye-movements.

Planning and guiding the return-sweep is associated with right FEF activation (Leff et al., 2000; Leff, Scott, et al., 2001) and depends on the extraction of line-length information from the left parafoveal visual field (McConkie & Zola, 1987). Left-sided parafoveal visual field loss impairs the accurate discrimination of the beginning of the line and, therefore, affects the visual guidance of the return-sweep. The observation that overly long lines disrupt the return-sweeps of normal readers supports this assumption (Gassel & Williams, 1963a; Rayner & Pollatsek, 1989). Gassel and Williams (1963a) reported that the return-sweep of their left-sided hemianopic patients improved after reading a few lines. In contrast to left-to-right reading saccades, the return-sweep's saccadic target, i.e. the first word of the next line, is almost always at a fixed horizontal position (most print text is left justified). After some practice with a text the spatial coordinates of the left text boundary might be represented within a higher-level framework, which may mitigate the effects of a left-sided parafoveal visual field loss on the visual guidance of the return-sweep.

5. Looking beyond parafoveal visual field loss: is hemianopic dyslexia purely visually elicited?

Poppelreuter (1917/1990) pointed out that “the impairment caused by the hemianopia itself is not that substantial” (p. 223), and “the disturbance of the co-ordination of the reading gaze-shifts” (p. 224) associated with hemianopic dyslexia may not be solely visually elicited. Examining adaptation processes in homonymous parafoveal visual field loss and the anatomical conditions that are responsible for the severe and long-lasting reading impairments in patients with hemianopic dyslexia will show that parafoveal visual field loss is a necessary yet not a sufficient condition that causes hemianopic dyslexia.

5.1. Hemianopic dyslexia and the question of spontaneous oculomotor adaptation

Moving masks and window studies with normal readers may suggest that hemianopic dyslexia is purely visually elicited. Visual masks or windows occluding either the foveal or parafoveal visual field produce reading impairments in normal readers similar to those caused by homonymous visual field disorders (Cummings & Rubin, 1992; Fine & Rubin, 1999a, 1999b, 1999c; Ikeda & Saida, 1978; McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Sowiacek, & Bertera, 1981).

Reading using parafoveal and peripheral vision, i.e. “reading without a fovea” (Rayner & Bertera, 1979), is almost impossible (see also Fine & Rubin, 1999a, 1999b, 1999c; Rayner et al., 1981) as is found by patients with a central scotoma (Teuber, Battersby, & Bender, 1960). Two single cases have been reported where reading speed was as low as 3 and 12 words per minute (see Zihl, 2000, pp. 151–164). Having to rely exclusively on foveal vision (reading without both parafoveas) also makes reading difficult. A one-letter moving window forces normal readers into letter-by-letter reading (Rayner & Bertera, 1979; Rayner et al., 1981), similar to the reading-style of pure alexics (Johnson & Rayner, 2007; Rayner & Johnson, 2005). The ‘natural’ counterparts of these experimental moving windows are bilateral homonymous visual field disorders, which affect both left and right parafoveal vision. Mackensen (1962) found the distinctive reading impairments of left- and right-sided parafoveal visual field loss appear in combination in such patients. Reading performance is worst in patients with a bilateral hemi-

anopia (tunnel vision) as their residual vision may be nothing else than a one-letter moving window (Zihl, 2000). Reading without a parafovea may be less difficult. Yet, obliterating the left or right parafoveal visual field in normal readers produces reading impairments similar to hemianopic dyslexia (Cummings & Rubin, 1992; Ikeda & Saida, 1978; McConkie & Rayner, 1975, 1976; Rayner et al., 1981; Rayner, Liversedge, & White, 2006).

One must not forget that if an artificial visual field defect is imposed the resulting reading impairments are not as severe and long-lasting as in hemianopic dyslexia. Normal subjects seem to adapt quickly to visual field loss (Poppelreuter, 1917/1990), although interindividual differences may be substantial (Zangemeister & Utz, 2002). Furthermore, not all patients with unilateral homonymous parafoveal visual field loss necessarily show impaired reading. Adequate reading performance was found in 16% (out of 50 cases) about six weeks after brain injury (Zihl, 1995a), and in 29% (out of 35 cases) when followed over a period of three years (Gassel & Williams, 1963a). Despite the prevailing parafoveal visual field defect, impaired reading performance as well as the concomitant abnormalities of the oculomotor parameters were no longer evident. Furthermore, Mackensen (1962) reported a case with a remarkable reading performance despite a severe right-sided homonymous hemianopia with only 0.5° visual field sparing. Such observations contradict the assumption that parafoveal visual field loss is the sole cause of hemianopic dyslexia and raise the question of the extent to which hemianopic dyslexia has a purely visual basis.

From his investigations Mackensen (1962) concluded that the severity of the reading impairment is not only determined by the presence of parafoveal visual field loss but also by whether and how well one has learnt to compensate for the visual defect. To overcome their visual impairment the most obvious solution for patients seems to be using appropriate eye-movement strategies. Patients consistently shift their gaze, thus their visual field border, into the area corresponding to their blind hemifield, thereby bringing obscured visual information briefly into the seeing field. It was Poppelreuter (1917/1990) who first reported spontaneous oculomotor compensation in visual field loss.

There is a consistent set of compensatory oculomotor strategies to which patients resort in order to cope with their lost part of the visual field. Targets located in the blind hemifield are approached with a safe-but-slow staircase strategy (series of small stepwise, hypometric saccadic eye-movements) especially if the target is unpredictable (Meienberg, Zangemeister, Rosenberg, Hoyt, & Stark, 1981). Most patients resort to such strategy, which is, however, time-consuming, laborious and simply insufficient to effectively compensate for parafoveal visual field loss (see also Poppelreuter, 1917/1990; Williams & Gassel, 1962; Zihl, 2000). They also employ this careful, safe-but-slow staircase strategy in reading (“beginning and end of line detective”)—their reading rate is considerably reduced, and the number of errors is increased, in comparison with normal readers. More efficient adaptive reading strategies are characterised by top-down guided, predictive overshooting saccades in the direction of the blind field (“blind hemifield overshooting”) (Meienberg et al., 1981; Zangemeister, Oechsner, & Freska, 1995; Zangemeister & Utz, 2002).

Such spontaneous adaptive strategies are, however, rarely found (Schoepf & Zangemeister, 1993). A common observation is rather that patients with homonymous visual field loss shift their head towards the affected side (Zihl, 2000). As head movements normally follow and depend on saccadic eye-movements (Uemura, Arai, & Shimazaki, 1980), reversing this normal physiological sequence to compensate for visual field loss is maladaptive and might even increase the resulting functional visual impairment (Kerkhoff et al., 1992). Although some patients with parafoveal sco-

tomas regain normal reading performance despite only 1–2° of visual field sparing, in the majority of patients reading impairments persist (Zihl, 2000). So, parafoveal visual field loss in itself cannot completely account for hemianopic dyslexia.

Consequently, there must be specific requirements for the ability to develop a compensatory eye-movement strategy with time (see also Kennard, 2002). Unquestionably, effective compensation implies some (implicit) knowledge of how to compensate (Zihl, 2000). Furthermore, learning to cope with a homonymous visual field loss and developing spontaneous compensatory strategies should require some time: “the complicated processes of compensation (...) can come to light as only slowly and gradually acquired improvements” (Poppelreuter, 1917/1990, p. 239). Evidence suggests that reading performance and the concomitant eye-movement parameters can improve with time after the onset of visual field loss (Gassel & Williams, 1963a). However, patients seem to either start very early spontaneously compensating for their parafoveal field loss or they do not regain normal reading performance even several weeks or months after their initial visual field loss (Zihl, 1995a). Thus, patients can be classified into two categories according to whether or not they develop spontaneous compensation strategies.

The decisive factor seems to be whether injury to the postchiasmatic visual pathway is accompanied by additional injury to the occipital white matter, occipitoparietal structures, or the posterior thalamus. Patients in which these structures are spared show very efficient spontaneous oculomotor compensation, notwithstanding very small degrees of visual field sparing. Even after posterior cerebral artery infarction extra-striate injury is the rule rather than the exception (Hebel & von Cramon, 1987), which may explain the high percentage of patients showing little or no spontaneous compensation (Zihl, 1995a). Support for this hypothesis stems from the fact that these structures and their reciprocal connections are assumed to be part of a cortical–subcortical network subserving the bottom-up and top-down control of visual–spatial attention and related saccadic eye-movements (Corbetta, 1998; Corbetta & Shulman, 2002), which may be crucial for the development of spontaneous compensatory oculomotor strategies. If the structures and interconnecting callosal fibre pathways of this network are spared, parafoveal visual field loss can be mitigated by a specific set of top-down controlled intentional saccades into the blind hemifield. As a consequence, the regular eye-movement pattern required for effective text processing can be regained (Zihl, 1995a).

5.2. Hemianopic dyslexia and its anatomical basis

From our knowledge of the anatomy of the retino-striate visual pathway, we can infer the anatomical loci in which damage gave rise to a specific pattern of visual field loss. Injury to central, i.e. postchiasmatic portions of the pathway leads to characteristic homonymous visual field defects, which can be predicted from the retinotopic organization of the pathway. Most commonly, lesions are located in the optic radiations and the striate cortex (Harrington, 1976; Zhang et al., 2006), typically resulting in a hemianopia with and without macular sparing. Injury to the posterior part of the optic radiations and the striate cortex results in congruous homonymous visual field defects, i.e. they share the same location, extent and shape in the two monocular visual fields. Incongruous and incomplete defects typically occur in cases with injury to the anterior parts of the postchiasmatic pathway (optic tract, lateral geniculate body, and the anterior part of optic radiation) (Harrington, 1976; Zihl & von Cramon, 1986).

However, although no empirical data are available, it appears reasonable to assume that for hemianopic dyslexia to emerge the locus of damage along the postchiasmatic visual pathway is not

decisive and has no differential effects on the resulting reading impairment. Hemianopic dyslexia can be caused either by injury to the optic tract, the lateral geniculate body, the optic radiation, or the striate cortex—presupposed this injury is accompanied by additional damage to the fibre pathways and/or structures constituting the neural network subserving the bottom-up and attentional top-down control of visual information processing and saccadic eye-movements in reading (Zihl, 1995a). Injury to the primary visual cortex (or its geniculostriate afferents) in itself (Leff et al., 2006) cannot completely account for hemianopic dyslexia.

So far, only one study has analysed the anatomical basis of hemianopic dyslexia (Zihl, 1995a). In a sample of 50 patients with left- or right-sided homonymous hemianopia, reading performance of patients whose brain injury was restricted to calcarine cortex (location of primary visual cortex) only (16% of patients) was close to normal (155 wpm; ~89% of normal reading performance, N : 175 wpm), and sufficient for their occupational and daily life. In cases with larger lesions involving the striate cortex and partially the occipital white matter (44% of patients) a moderate reading impairment was found (108 wpm; ~62% of normal reading performance). Extensive unilateral injuries involving the occipital white matter (in 26% of patients) and the posterior thalamus (in 14% of patients) resulted in a severe and long-lasting reading impairment and pronounced visual handicap (56 wpm; ~32% of normal reading performance) (Zihl, 1995a).

Reports of three single cases with right-sided homonymous hemianopia (visual field sparing: 2°) further confirm and illustrate more clearly that hemianopic dyslexia is not purely visually elicited (Zihl, 1995a). Despite showing the same visual field defect and the same field sparing, these patients differed greatly with regard to their reading speed (A: 120 wpm; B: 82 wpm; C: 32 wpm). In addition, they did not differ with regard to age (A: 50 years; B: 46 years; C: 46 years) nor time since lesion (A: 8 weeks; B: 9 weeks; C: 14 weeks). Although patient C had the longest time since lesion, and thus the longest time to adapt to his defect, he nevertheless showed the most severe reading impairment. A comparison of their underlying lesions revealed that in patient A, who showed almost normal reading performance, the lesion was restricted to calcarine cortex; in patient B, who showed a moderate reading impairment, occipital white matter was, in addition, partly affected; in patient C, whose reading impairment was worst, a major portion of the occipital white matter and the posterior thalamus were affected. The same finding was reported for three patients (D, E, F) with left-sided homonymous hemianopia (LH; 2°) (Zihl, 1995a).

The pronounced differences in reading speed between right- and left-sided parafoveal visual field losses seem to diminish if the extent and site of lesions is controlled for when making the comparison. The lesions of patient A (RH) and D (LH; age: 46 years, time since lesion: 7 weeks) were restricted to calcarine cortex, and both showed almost normal reading performance with almost similar reading speeds (A: 120 wpm; D: 105 wpm); Patient B (RH) and E (LH; age: 52 years, time since lesion: 8 weeks) had both partly occipital white matter involvement and showed a similar reduction in reading speed (B: 82 wpm; E: 87 wpm). Patient C (RH) and F (LH; age: 58 years, time since lesion: 9 weeks) showed both extensive occipital white matter involvement and a severe reading impairment. Yet, the greater reduction of reading speed in patient C (32 wpm; F: 68 wpm) cannot be fully explained by the difference between right- and left-sided parafoveal visual field loss—the additional involvement of damage to the posterior thalamus in patient C has to be taken into account (Zihl, 1995a).

The posterior thalamus and its connections to the occipital, parietal and frontal lobes, and the limbic neocortex are involved in the visual guidance of eye-movements (Ogren, Mateer, & Wyler, 1984; Robinson & Petersen, 1992; Zihl & von Cramon, 1979). Injury to

the occipital white matter might damage the fibre pathways which connect the visual areas of the brain to motor areas for the visual control of eye-movements. In addition to the cortico-cortical fibre connections between visual, parietal and frontal areas, the subcortical pathways connecting visual cortical areas and pontine cells, which also receive input from the superior colliculus, may also be affected by damage to the occipital white matter (Glickstein, 2000).

Injury to the striate cortex or its geniculostriate afferents, the occipital white matter comprising subcortical-cortical reciprocal connections, and/or the posterior thalamus, causes parafoveal visual field loss. These injuries may impair, to varying degrees, the bottom-up and attentional top-down control of visual information processing in the fovea and parafovea and the eye-movements involved in reading. Lesions that are confined to calcarine cortex result in parafoveal visual field loss which may disturb visual information processing and bottom-up oculomotor control (Leff et al., 2000). However, restricted calcarine cortex lesions preserve the neural network that mediates efficient visual processing and related oculomotor processes from the top-down. Intact attentional top-down control can facilitate visual information processing and the guidance of eye-movements into the blind field via feedback connections. The interactive flow of activation between V1/V2 and parietal as well as frontal cortical regions via feedforward (bottom-up) and feedback connections (attentional top-down modulation of V1/V2) supports such view (Foxy & Simpson, 2002; Hochstein & Ahissar, 2002; Juan & Walsh, 2003). Where top-down attentional mechanisms are intact, an oculomotor strategy can be developed and adjusted to compile a complete percept of each word, even though each fixation provides only an incomplete view. Spontaneous oculomotor adaptation efficiently substitutes the lost visual field region via top-down processing and the ability to read remains more or less intact (Zihl, 1995a, 2000).

Evidence on the anatomical basis of hemianopic dyslexia allows us to conclude that this reading impairment is more than purely visually determined. Hemianopic dyslexia is not caused by parafoveal visual field loss resulting from unilateral postchiasmatic injury alone. Severe and long-lasting saccadic eye-movement abnormalities in reading and related impairments of text processing require widespread damage to the distributed neural network subserving the bottom-up and attentional top-down control of visual information processing and saccadic eye-movements in reading. In contrast, patients with sparing of the structures belonging to this neural network usually compensate for their parafoveal visual field loss and show a close to normal reading performance. The high frequency of combined striate/white matter lesions in patients with homonymous visual field defects (Hebel & von Cramon, 1987) nevertheless justifies the further usage of the term hemianopic dyslexia to characterize this special type of reading impairment (Zihl, 1995a).

Our current knowledge of the anatomical basis of hemianopic dyslexia is based on an analysis of CT and MRI scans (Zihl, 1995a). These methods may underestimate the extent of lesions. An unilateral lesion to the optic radiation or striate cortex might change glucose metabolism in the intact ipsilateral thalamus and visual association areas as revealed by PET studies (Bosley et al., 1985). Such 'remote' effects are interpreted as interruption of the fibre pathways interconnecting both structures, which leads to a deactivation of the primary intact structure (Grüsser & Landis, 1991). These effects have to be differentiated from primary lesion sites for a valid interpretation of behavioural deficits and for developing a model of the functional organisation of the processes underlying complex behaviour such as reading (Zihl, 1995a). Consequently, we may (re-)interpret the effects on reading-related PPC and FEF activation patterns in patients with right-sided homonymous hemianopia (Leff et al., 2000). Preparation of reading saccades

may not be disrupted solely by right-sided hemianopia arising from left V1/V2 damage. It is also possible that fibres connecting cortical visual areas with parietal and frontal areas may have been affected in these patients.

6. The rehabilitation of hemianopic dyslexia: re-learning eye-movement control in reading

Poppelreuter (1917/1990) was the first who systematically attempted training patients with hemianopic dyslexia to learn, or re-learn, oculomotor control in reading. He showed convincingly that in patients with a lost parafoveal visual field "relearning of reading was successful" (p. 249). As Poppelreuter (1917/1990) said, the main goal for patients is "to make the preserved paracentral portion (...) a field for reading" and to move "the location of the position of the clearest vision further to the right or to the left" (p. 248). He taught his patients to use a wooden reading stick which they moved successively from word to word of the text they read off a board. Patients with a right-sided visual field loss were asked to place the reading stick at the end of the word that is currently being read, patients with a left-sided defect had to place it at the beginning of words. Patients therefore learn to shift their attention and gaze intentionally into their blind field. After a few weeks of training, hesitant reading gave way to regular reading with correct intonation (a valuable behavioural indicator of rehabilitation of hemianopic dyslexia, see Mackensen, 1962; Zihl, 2000), and difficulties in identifying words and text comprehension were reduced. Reading speed increased and errors were reduced (Poppelreuter, 1917/1990).

Gassel and Williams (1963b) also found that the refinement and employment of attentional and gaze-shifts are the basis for oculomotor compensation in patients with homonymous visual field defects. To regain reading performance, patients have to intentionally shift their gaze further than they can actually see, i.e. into their blind field, so that they can perceive the entire word or text passage again; they learn "to keep the 'blind side' in sight" (Zangemeister & Oechsner, 1999, p. 89). Well-timed gaze shifts can re-establish the temporal and spatial coherence of successive extracted parts of visual information, which leads to the experience of seeing words at one glance again (Zihl, 1995a). Intentionally shifting attention and gaze so as to perceive each word as a whole before reading it is of particular importance in ameliorating word processing and identification difficulties. It is crucial that patients learn to visually apprehend before comprehend a word (Zihl, 2000).

Although Poppelreuter's (1917/1990) wooden reading stick has not stood the test of time, the rationale behind his quirky procedure is still valid. It has survived in form of a compensatory treatment approach for rehabilitating patients with hemianopic dyslexia using, instead of a wooden stick, an electronic reading aid with gliding text (Zihl, 1995a; Zihl et al., 1984). An alternative yet more flexible and efficient treatment method is the PC-based, tachistoscopic presentation of text material (Zihl, 2000). Regular and systematic massed practice allows new oculomotor strategies to be consolidated into flexible oculomotor reading routines (Ofen-Noy, Dudai, & Karni, 2003). Over-learning gradually leads to the 'automatization' of this strategy and hence comfortable reading (see also Bäckman, 1999).

Eye-movement recordings after only a few training sessions (about 10–15 sessions, 45 min) reveal more or less normal oculomotor reading patterns and reading performance in the majority of cases (Zihl, 1995a, 2000). Overall, patients make fewer and shorter fixations, and show fewer regressions and refixations within words. The amplitude of rightward saccades increases especially in right-sided visual field loss. Patients with left-sided field loss make larger

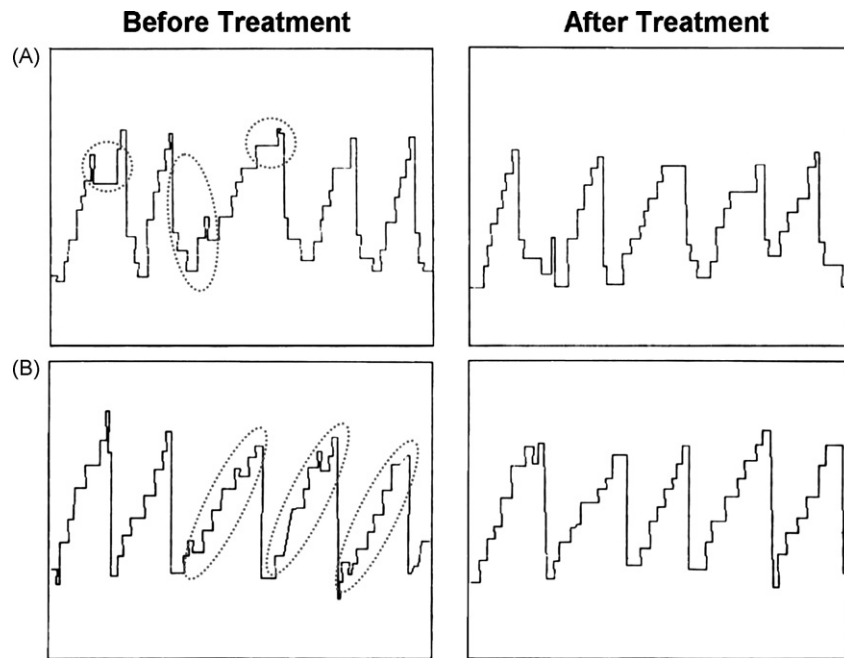


Fig. 5. Infra-red eye-movement recordings before and after treatment in patients with left- (A) or right-sided (B) unilateral homonymous hemianopia (field sparing: $\sim 3^\circ$). Eye-movement patterns during reading of five lines are shown (x-axis: time period of recording; y-axis: horizontal extension of line from left to right). (A) Note the prolonged fixations and regressions (ovals) as well as the interrupted return sweep (ellipse) before and the normalisation of the oculomotor pattern after treatment. (B) Note the distorted left-to-right oculomotor reading pattern (prolonged fixations, smaller forward saccades, and regressions (ellipses)) before and its normalisation after treatment. Eye-movement recordings are adapted from Zihl (1995a).

leftward saccades (return-sweeps) (see Fig. 5) (Zihl, 1995a, 2000). Reading fluency is regained; reading speed increases (before treatment: 76 wpm (LH), 53 wpm (RH); after treatment: 113 wpm (LH), 96 wpm (RH) (Zihl, 1995a)) and fewer errors are made. Follow-up assessments show that these treatment effects remain stable (Kerkhoff et al., 1992; Spitzyna et al., 2007; Zihl, 1995a, 2000). After treatment, reading performance in hemianopic dyslexia is markedly improved although parafoveal vision is still lost. Re-organizing oculomotor control is decisive for making our 'optical instruments' useful once again for reading (Gassel & Williams, 1963b).

Most patients benefit from systematic oculomotor practice. Patients with right-sided parafoveal visual field loss, however, require almost twice as much training sessions than patients with a similar left-sided field loss. Even then, they still show a poorer outcome in comparison with patients with left-sided field loss (Zihl, 1995a, 2000). The differential or "asymmetrical" effect of left- and right-sided parafoveal visual field loss on rehabilitation outcome appears to be specific to reading. When scanning a visual scene there are no performance differences between left- and right-sided visual field defects as in reading (Tant et al., 2002; Zihl, 1995b, 1999). Furthermore, oculomotor scanning performance, in contrast to reading performance, is not associated with the degree of visual field sparing in such a way that the smaller the sparing, the more impaired is oculomotor scanning. Also the location of the visual defect within the visual field is much more important in determining the resulting reading impairment than the scanning impairment (Poppelreuter, 1917/1990; Zihl, 1995b). Wilbrand (1907) reported that small paracentral scotomas only posed an impediment to reading but not to exploring surroundings in his patients. Furthermore, spontaneous oculomotor adaptation to a homonymous visual field disorder in visual exploration is more likely (40%) than compensating for the reading impairment ($\sim 20\%$). In addition, both abilities seem to require specific training for their improvement and there appears to be no obvious transfer effect

between both domains. One may speculate that the control of the oculomotor scanpath for reading is mediated by different neural networks than the scanpath for visual exploration, although both networks probably overlap (Zihl, 1995a, 1995b, 2000).

The effect of top-down text processing strategies on inter- and intraindividual variation in reading ability might be marginal in normal readers (see O'Regan, 1992). Yet, differences in factors such as self-control may be crucial when a new reading strategy has to be learnt. 'Risky' readers (who flexibly deploy fewer fixations over a larger span of words) often adopt new strategies to cope with visual field loss more quickly than 'cautious' word-by-word readers do (although possibly at the expense of omitting words or syllables).

Rehabilitation of hemianopic dyslexia depends on perceptual and oculomotor (i.e. procedural) learning processes. Learning and consolidation of new oculomotor reading strategies are top-down guided and modulated by attention. PPC function may play an important role in mediating these learning processes. Right PPC is crucial for perceptual learning and attention, and practice-related decrease of activation has been observed for the practice of visual search tasks (Walsh, Ashbridge, & Cowey, 1998; Walsh, Ellison, Ashbridge, & Cowey, 1999).

That patients with additional extensive injuries to the occipital white matter and/or to occipitoparietal regions require the largest amount of training (Zihl, 1995a, 2000) also indicates the relevance of parietal mechanisms for the rehabilitation of hemianopic dyslexia and demonstrates the importance of intact functional connections between the cortical visual areas and the areas that supposedly mediate the treatment effect.

Interestingly, patients with normal visual fields but posterior parietal damage reported difficulties in finding their way through lines of text on a page (Zihl & Hebel, 1997). Comparing this reading impairment to the reading difficulties of patients who have a similar posterior parietal involvement but an accompanying unilateral homonymous parafoveal visual field loss could illuminate the relative contributions of attentional posterior parietal and sen-

sory striate cortex functions to reading and also to learning new oculomotor reading strategies.

Further evidence for PPC involvement stems from a recent investigation of brain representation of visually guided saccades in a small group of patients with pure striate cortex lesions resulting in right- or left-sided homonymous hemianopia. These patients showed no impairments of visual exploration or reading. Making saccades to targets presented in the intact and compromised hemifield was associated with a bilateral activation of the frontal and parietal eye fields, albeit to a lesser degree than in normal observers. Increased activation in patients was found in the posterior parietal cortex of the unaffected hemisphere, i.e. contralateral to the side of the intact hemifield, suggesting that visual field defects after striate lesions are associated with changes in the fronto-parietal network underlying the cortical control of saccades. Whether this activation represents a neural correlate of (spontaneous and/or training-induced) oculomotor compensatory processes needs further study (Nelles et al., 2007).

Mirror reading provides further insights into the involvement of parietal and also frontal mechanisms in the rehabilitation of hemianopic dyslexia. The acquisition of mirror-reading skill in normal subjects is associated with changes in activation patterns of posterior brain regions and stronger activation in the parietal associative cortex and the frontal eye fields. After training when reading strategies have been learned successfully and become routine, a practice-related decrease of activation in prefrontal and posterior parietal areas is observed (Kassubek, Schmidtke, Kimmig, Lücking, & Greenlee, 2001; Poldrack et al., 1998; Poldrack & Gabrieli, 2001). Prefrontal cortex activity is critical for procedural learning (Beldarrain, Grafman, Pascal-Leone, & Garcia-Monco, 1999; Jueptner et al., 1997; Miller & Cohen, 2001) and the FEF in particular are involved in intentional, voluntary generated attentional and eye-movement shifts according to a rule (Heinzle et al., 2007).

Many assumptions about the underlying mechanisms of the resulting improvement in rehabilitation of hemianopic dyslexia must remain speculative without evidence from functional neuroimaging. Nevertheless, the finding that the lost parafoveal visual field region can be successfully substituted by spontaneous or training-induced oculomotor adaptation shows the functional plasticity of the visual, attentional and oculomotor systems and their underlying neural mechanisms involved in text reading. Reading eye-movements can be controlled either from bottom-up (parafoveal visual field) or via an attentional top-down text processing strategy.

7. Synopsis: insights from and into hemianopic dyslexia

A great deal has been learnt about hemianopic dyslexia since it was first reported by Mauthner in 1881. Studying patients with hemianopic dyslexia offers important insights into the normal reading process and its neural basis, which may be useful in informing theories and models of reading and eye-movement control. Hemianopic dyslexia is a special type of reading impairment that is caused by injury to systems subserving the bottom-up and attentional top-down control of visual information processing in the foveal and parafoveal visual field and saccadic eye-movements involved in reading. The anatomical basis of hemianopic dyslexia involves left- or right-sided injury to the striate cortex or its geniculostriate afferents compromising the representation of parafoveal vision. Yet, the critical lesion location for the severe and long-lasting reading impairments lies elsewhere. It is in the fibre pathways that reciprocally connect the visual areas of the brain to the parietal, frontal, and temporal areas, as well as to the subcortical areas

involved in the control of visuospatial attention and the guidance of the scanpath in text processing.

Hemianopic dyslexia provides valuable neuropsychological insights into the neural mechanisms essential for normal reading. It shows that the visual field is not only a sensory surface or passive information intake zone but “as much a measure of the attention (...) as of the anatomical substrate” (Williams & Gassel, 1962, p. 243). Visual information processing in reading requires attentional top-down control which, together with higher-level linguistic processes, facilitates visual processing at the early stages of the reading process for word identification and eye-movement control. Such careful coordination of visual information processing, eye-movement control, visuospatial attention, and linguistic processing requires coordinated parallel processing in multiple cortical brain regions supported by large-scale neural networks.

Hemianopic dyslexia shows that parafoveal vision is crucially involved in reading although it is not absolutely essential. It is crucially involved insofar as it subserves word processing and identification and the visual guidance of reading eye-movements. Obliterating parafoveal vision, either by injury to the striate cortex or its geniculostriate afferents or by experimental masks in normal subjects impairs text processing and alters the oculomotor reading scanpath from bottom-up. Furthermore, the side and extent of the artificial or natural visual field defect determine, together with the functional demands of the writing system and the reading task *per se*, the quality and severity of the resulting reading impairments. Purely visually elicited impairments are, however, not severe or long-lasting. The guidance of reading eye-movements can be adjusted to re-establish sufficient visual information processing for reading to proceed in a regular fashion, although each fixation still only provides an incomplete view. An attentional top-down control of visual sampling can successfully ‘substitute’ parafoveal vision. The representation of parafoveal vision in striate and prestriate cortex may not be essential to reading in so far as its (artificial or brain injury-related) loss can be compensated for. Parafoveal visual field loss is a necessary yet not sufficient component for the emergence of hemianopic dyslexia.

Successful spontaneous and training-induced oculomotor compensation for parafoveal visual field loss in reading suggests that there is a discrepancy between involvement and absolute necessity of the cortical and subcortical areas involved in reading. This discrepancy demonstrates the functional plasticity of the visual, attentional and oculomotor systems involved in reading and “may reflect significant functional reserve and plasticity within the cortical network as a whole” (Leigh & Kennard, 2004, p. 474). Oculomotor adaptation to parafoveal visual field loss in reading requires intact attentional and oculomotor systems along with their reciprocal connections to visual areas. These systems and their inter-connections form a distributed network that subserves visuomotor integration and the attentional top-down modulation of visual information processing which are required for reading. This network is therefore not only involved but necessary for normal reading to occur. It consists of visual cortical, parietal (esp. PPC) and frontal (esp. FEF) areas.

If, in addition to unilateral homonymous parafoveal visual field loss, the functional connections within this network, and hence the functioning of its components, are affected by brain injury, hemianopic dyslexia results. The level of functioning of this network determines the extent to which the residual visual field can be utilised via a top-down attentional strategy for word identification and guiding reading eye-movements. Depending on which network components are affected as well as which part of the visual field and how much of it is spared, hemianopic dyslexia is more or less severe and qualitatively different reading impairments result. Hemianopic dyslexia demonstrates the importance to reading of white matter

pathways reciprocally connecting the foveal/parafoveal parts of V1 with the parietal, frontal, and temporal cortices and the subcortical areas involved in saccade control. Despite different contributions of parietal and frontal areas to the control of saccadic activity, both areas and their close cooperation are essential in sampling the visual world in reading. Hemianopic dyslexia may be interpreted best as a *visual–attentional–oculomotor–network disorder*.

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