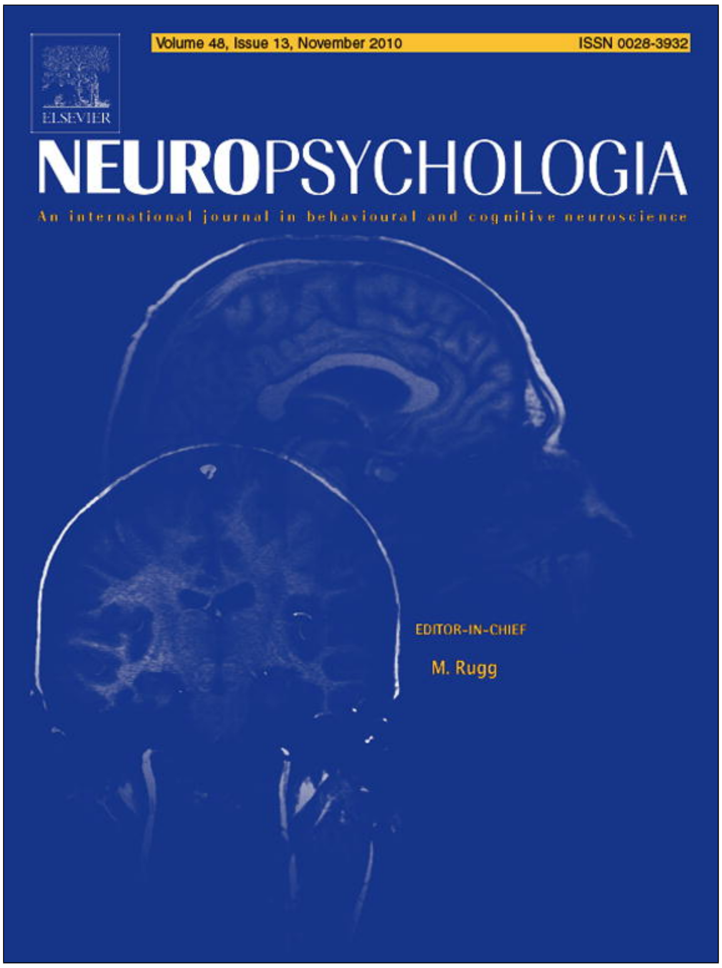
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# Effects of head rotation on space- and word-based reading errors in spatial neglect

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ABSTRACT

Patients with right hemisphere lesions often omit or misread words on the left side of a text or the beginning letters of single words which is termed neglect dyslexia (ND). Two types of reading errors are typically observed in ND: omissions and word-based reading errors. The prior are considered as space-based omission errors on the contralesional side of the page, while the latter can be viewed as a kind of stimulus- or word-based reading errors where leftsided parts of a single perceptual entity (the word) are neglected. The head, trunk and eyes are part of a hypothetical egocentric reference frame that is aligned around our body and divides space into a left and right hemispace. Previous neglect studies have shown that head- and trunk-orientation significantly influence contralesional neglect. An open question is whether such egocentric manipulations also influence omissions and word-based errors in *paragraph* reading in ND. The current study investigated in a sample of right-hemisphere lesioned patients with ND vs. without ND and matched healthy control subjects the influence of head-rotation (HR) on both types of reading errors using controlled indented paragraph reading tests. Passive leftward HR significantly reduced omission errors on the left side of the text in ND, but had no effect on word-based reading errors. In conclusion egocentric manipulations like HR only appear to influence space-based attentional processes in neglect evident as omissions in paragraph reading but have no impact on those attentional processes involved in word identification evident as word-based errors in paragraph reading.



## 1. Introduction

Patients with unilateral brain lesions often show a conspicuous syndrome where they do not report or respond to stimuli presented in the contralesional hemispace in the absence of elementary sensory or motor deficits, termed neglect. Neglect is a multi-componential, heterogenuous syndrome that entails several different aspects (Halligan, Fink, Marshall, & Vallar, 2003). *Egocentric* neglect phenomena represent a category of various kinds of neglect where the reference frame is based on a midline projected from the body (Driver & Pouget, 2000). Importantly, there can be multiple frames of reference based on the body parts from where these midlines are projected (i.e. trunk, head, eyes, etc.). Hence, egocentric neglect phenomena concern the failure of the patient to attend to contralateral stimuli in space in relation to the midsagittal plane of the patient's body or certain body parts (Ventre & Flandrin, 1984). Typically, neglect patients show severe impairments in many egocentric tests of neglect that have been conducted so far (i.e. cancellation, visual and tactile exploration, writing, see for review Chokron, Dupierrix, Tabert, & Bartolomeo, 2007).

Another component of neglect is termed allocentric or object-centered neglect where the contralesional side of a single perceptual object is neglected irrespective of its location in space. Clinically, neglect patients often show impairments in object-centered neglect tasks such as drawing a symmetrical figure, perceiving or copying a face or eating from a plate (Halligan et al., 2003). Here, in contrast to egocentric neglect phenomena the patient's body (trunk, head, eyes, etc.) does not serve as a midline reference for the performance in these tasks, and therefore these impairments may occur with a similar frequency in both hemispaces.

Several studies have shown that ego- and allocentric neglect phenomena are dissociable and rely on different neural structures. Recent evidence has shown that allocentric or object-centered cancellation deficits (on the left side of *every* stimulus) were found after right superior temporal gyrus lesions whereas left egocentric neglect phenomena in the same cancellation task (omissions of stimuli in the left half of a page) were found after right pari-

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etal lesions (Hillis et al., 2005). In a related study (Ptak & Valenza, 2005) it was found that neglect patients with lesions involving the right inferior temporal cortex showed steeper left–right gradients in visual search for "object-like" displays. For these patients the left side of visual objects was more difficult to analyze, thus adding evidence to the role of right temporal cortex in object-centered visual processing. Convergent findings were obtained in another study (Grimsen, Hildebrandt, & Fahle, 2008). These authors studied visual search with specific displays and found that neglect-related impairments in an egocentric variant of their search tasks were associated with damage to the premotor cortex involving the frontal eye fields, while allocentric, object-centered neglect-related deficits were associated with lesions to ventral stream regions near the right parahippocampal gyrus. Taken together, these studies are consistent with the hypothesis that egocentric visual information processing is linked primarily to parieto-frontal brain areas in the dorsal stream (Vallar et al., 1999) whereas allocentric, object-centered visual processing is linked more closely to the areas in the ventral visual stream (Hillis et al., 2005; Honda, Wise, Weeks, Deiber, & Hallett, 1999; Verdon, Schwartz, Lovblad, Hauert, & Vuilleumier, 2010).

In line with these dissociations based on different reference frames (egocentric vs. allocentric) task-dependent dissociations are often found in spatial neglect (Binder, Marshall, Lazar, Benjamin, & Mohr, 1992). These authors reported task-dependent anatomical dissociations in a group of 34 patients with right-hemisphere stroke. While patients with posterior lesions were mainly impaired in horizontal line bisection patients with frontal or deep lesions showed largely normal line bisection but impaired letter cancellation performance. Moreover, no significant correlation ($r = .39$) was obtained between both tasks in their patient group. These findings suggest separable components of the neglect syndrome which result from damage to discrete areas in the right cerebral hemisphere.

### *1.1. Neglect dyslexia (ND)*

In addition to ego- and object-centered neglect phenomena in visual cancellation or visual search tasks, patients with spatial neglect often show impairments in reading termed neglect dyslexia (ND). During reading of *single* words these patients omit or substitute contralesional letters, syllables or half of a compound word (Behrmann, Moscovith, Black, & Mozer, 1990; Caramazza & Hillis, 1990; Ellis, Flude, & Young, 1987; Haywood & Coltheart, 2001; Ladavas, Umilta, & Mapelli, 1997; Riddoch, 1990). This feature of the neglect syndrome is considered to be a peripheral type of reading deficit induced by left-sided body-centered or object-centered inattention (Lee et al., 2009). During paragraph or text reading neglect patients often show omissions on the contralesional side of the text, and in addition word-based errors like omission of syllables or substitutes of leftsided letters within *single* words or substitutions of whole words.

The intensive research on single word reading in ND in the past two decades (see references above) has provided many important insights into the mechanisms of single word reading (Ellis et al., 1987), spared and impaired levels of performance in ND (Ladavas et al., 1997), the nature of object-centric "word-form" representations in the brain (Caramazza & Hillis, 1990), the identification of viewing-position effects (Stenneken, van, Keller, Jacobs, & Kerkhoff, 2008) as well as associations and dissociations with other forms of visuospatial neglect (Lee et al., 2009), to name only a few advancements in this field of research. In contrast to this huge progress in word-identification mechanisms in neglect dyslexia *paragraph reading* has been studied surprisingly rarely in ND up to now. Although paragraph or text reading subtests are often part of standard neglect screening batteries (see for instance the Behavioural Inattention Test, Halligan, Marshall, & Wade, 1989; Wilson, Cockburn, & Halligan, 1987) or the extensively validated French GEREN/GRECO neglect test battery (Azouvi et al., 2002), only few studies have so far dealt with the mechanisms of paragraph reading in comparable depth as those investigating single word reading in ND. Studies using the "Indented paragraph reading test" (Bachman, Fein, Davenport, & Price, 1993; Caplan, 1987; Towle & Lincoln, 1991) all have shown its high diagnostic sensitivity for neglect, partially because the indented margin on the left side requires frequent refixations by the patient. But even in these three studies mainly contralesional omissions were considered as dependent measures.

In an oculographic study of ND (Behrmann, Black, McKeef, & Barton, 2002) the authors had their patients read single words distributed randomly on a visual display comparable to a visual search task. Apart from reporting task-dependent dissociations of ND and visuospatial neglect they provided evidence that omitted (contralesional) words were often not fixated properly, while ipsilesionally presented words that were correctly read often were too often fixated. This dysfunctional oculographic pattern of results suggests a low-level visual impairment (i.e. eye-movement deficits) as one important source of reading errors in ND. Finally, in a recent treatment study we found that omissions in paragraph reading could be significantly reduced after repetitive optokinetic stimulation therapy whereas word-based neglect-related errors (i.e. substitutions, omissions of syllables within *single* words) persisted unchanged after treatment (Kerkhoff, Keller, Ritter, & Marquardt, 2006). This indicates that sensory stimulation do influence space-based or egocentric neglect phenomena as evident in the form of omission errors in reading but obviously failed to influence word-based errors in the same task in ND. This finding might also have implications for treatment because other novel therapies seem to be required if recent sensory stimulation techniques (Kerkhoff, 2003) are ineffective for the treatment of word-based errors in ND.

To sum up, much progress has been made in the past two decades in the understanding of the mechanisms involved in *single word reading* in ND. In contrast, less is known about the mechanisms involved in *paragraph reading* in ND apart from the fact that neglect patients are impaired in such tasks (see above). Even if one adopts the view that paragraph reading is not part of ND in a narrow sense but simply reflects spatial neglect it is indisputable that it is ecologically much more relevant for most of us than reading of single words presented in isolation. Paragraph or text reading is necessary in many different situations of daily living, including reading of a book, a newspaper, a journal article like this one, advertisements or a menu in a restaurant. Moreover, while studies involving single word reading have the clear advantage of allowing easy experimental control of relevant task variables (i.e. word length, frequency, etc.), paragraph reading allows to study both types of reading errors (omissions and word-based reading errors) in a more natural situation and may help to identify modulating factors. In turn, such findings might improve our understanding of the attentional mechanisms involved in paragraph reading in neglect patients.

The aim of the present study was therefore to analyse the influence of head-rotation (HR) – a well-known and effective manipulation of the egocentric reference (Chokron et al., 2007; Kerkhoff, 2001) – on omissions and word-based reading errors in right-hemisphere lesioned patients with ND, right-hemisphere lesioned patients without ND, and matched healthy normal subjects. While manipulations of the egocentric reference by modifications of head- or trunk-position (Karnath, Schenkel, & Fischer, 1991) or neck–muscle vibration (Schindler & Kerkhoff, 2004) have been shown to influence sensory neglect significantly only few experiments have investigated up to now their effect on reading. Interestingly, passive contralesional head-rotation by 20° as well as trunk-rotation by 20° significantly reduced ND in reading *single* words presented tachistoscopically in the center of the visual field (Schindler & Kerkhoff, 1997). Notably, the effects of head and trunk orientation were nearly equivalent in this study, suggesting comparable contributions.

The present study therefore addressed the following issues:

(i) Do modifications of the egocentric reference via manipulations of HR influence *both* types of reading errors (omissions and word-based errors)?
(ii) What is the quantitative relationship between the two types of reading errors in paragraph reading, and are there hemispace (left–right) differences in their frequency?

## 2. Methods

### 2.1. Subjects

Nine patients with right-hemispheric, vascular brain lesions and moderate to severe leftsided, visual neglect according to the results of conventional neglect screening tests (see below, Section 2.2) were included. Furthermore, another group of seven patients with vascular, right-hemispheric brain lesions without visual neglect in the same screening tests and comparable clinical and demographic criteria was investigated (see Table 1). In addition, 9 healthy subjects without brain damage (6 male, 3 female, age range: 33–67, mean age 46 years) were recruited. All subjects had a decimal visual acuity of at least 0.70 (20/30 Snellen equivalent) for the near viewing distance (0.4 m) and were appropriately corrected during the experiment. Moreover, all subjects had at least 9 years of education.

### 2.2. Visual field and visual neglect assessment

Kinetic monocular perimetry was performed in the majority of patients ($N = 12$) with a Tuebingen perimeter (Aulhorn & Harms, 1972) with a bright white stimulus (size: 106 min of arc of visual angle, luminance: 102 cd/m$^2$), a grey stimulus (106 min of arc of visual angle, 1.02 cd/m$^2$), a coloured target (green 525 nm, same size, 320 cd/m$^2$), and a form target (white light, same size, rhomboid, 320 cd/m$^2$). Kinetic perimetry was performed along all meridians in a pseudorandom order. Visual field sparing is indicated in Table 1 for the left horizontal meridian. In the remaining four patients kinetic Goldmann perimetry was performed monocularly with the largest test stimulus (V4) in the same way as described above.

Visual neglect was tested with three conventional tests, most of them very similar to those of the Behavioural Inattention Test (Halligan et al., 1989; Wilson et al., 1987): clock drawing from memory, figure copy (star, flower, cube) and paragraph reading of a 180-word reading test (Kerkhoff, Münβinger, Eberle-Strauss, & Stögerer, 1992). All screening tests were shown on a 29.7 cm × 20 cm white paper board – perpendicular to the patient's trunk midline – and at a distance of 0.33 m from the patient's eyes who wore his correction when required.

### 2.3. Experimental reading tests

As indented paragraph reading tasks are a highly sensitive measure of reading in neglect (Bachman et al., 1993; Caplan, 1987; Towle & Lincoln, 1991) and are not confounded by differences in education (Bachman et al., 1993) we constructed 45 short reading texts (mean length: 51.7 words, range: 43–65; arranged in 8–10 lines) of different length from two story books. The margins of each text were irregularly indented on *both sides* in order to enable comparisons of errors on the left vs. right text side; see examples in Appendixes A and B. Eight to ten words on every margin (left and right side) of each text were filler words and were not necessary for the semantic context of the text. This increases the sensitivity of the tests in ND. All texts were parallelized according to length (number of words, letters and lines), spatial arrangement and complexity as judged by the performance of the normal subjects. Each text was displayed sequentially one by one within a 8° × 12° large rectangular white field on a 17-in. computer screen. Texts were presented in black print (Arial, point size 22) on a white background at a distance of 0.5 m to the patient's eyes. The number of words displayed on each side of the reading texts was balanced (mean length left: 25.8 words, mean length right: 26.00 words). There was no statistical significant difference between the number of words presented on the left and right text side [$t(88) = 0.34$, $p = 0.73$].

### 2.4. Experimental conditions

The sequence of the experimental conditions was the following: the first and last experimental session served as baseline tests (Baseline 1, Baseline 2 with the head straight (0°)). This was done to control for possible learning effects throughout the study. The sequence of the second and third experimental session was balanced: in half of all subjects head-rotation to the left (20°) was followed by head-rotation to the right (20°), and vice versa in the other half of the subjects (see Fig. 1).

Under all conditions the subject's head was fixed in a head- and chin-rest and held there by one experimenter while the other preceded with the stimulus presentation. The subjects were instructed to read aloud everything they saw on the monitor in front of them. Reading was recorded with a tape-recorder for later off-line analysis, and simultaneously scored on a paper printout of the same texts displayed on the monitor. Five reading texts were presented during each experimental condition, their data were collapsed for each condition. Before starting the experiment two sample texts were presented to familiarize the subject with the procedure; these trials were not scored. No reading text was presented twice to any subject to exclude memory effects.

**Table 1**
Clinical and demographic data of 9 patients with left visual hemineglect due to a single vascular lesion of the right cerebral hemisphere (A, subjects $N+1$ to $N+9$), and 7 patients with a single right hemispheric infarction without leftsided visual neglect (B, $N-1$ to $N-7$). *Abbreviations*: ICB: intracerebral bleeding; MCI: middle cerebral artery infarction; BG: basal ganglia; MCA/PCA: middle cerebral artery infarction; L/R: left/right; Visual field: field sparing is indicated in (°) on the left horizontal meridian in the blind field. Neglect screening tests: paragraph reading of a 180 word reading test: cutoff max 2 errors, figure copy: − = omissions or distortions; + = normal performance; cancellation: number of omissions on the left/right side of the page; normal cutoff: max 1 omission per side.

| Subject | Visual neglect | Age, sex | Etiology | Months post lesion | Lesion location | Field defect, field sparing (°) | Figure copy Left/right side | Clock drawing Left/right side | Reading (% errors) |
|---|---|---|---|---|---|---|---|---|---|
| A: Right brain damaged patients with left visual neglect | | | | | | | | | |
| $N+1$ | Yes | 55, f | ICB | 9 | Parietal | Left hemianopia, 5° | −/+ | −/+ | 20 |
| $N+2$ | Yes | 55, m | MCI | 4 | Thalamus, parietal | Normal | −/− | −/+ | 33 |
| $N+3$ | Yes | 61, m | MCI | 3 | Temporal | Left hemianopia, 1° | −/+ | −/+ | 10 |
| $N+4$ | Yes | 55, f | MCI | 3 | Parietal, temporal | Left hemianopia, 5° | −/+ | −/+ | 8 |
| $N+5$ | Yes | 60, m | MCI | 4 | Parietal | Left hemianopia, 30° | −/+ | +/+ | 22 |
| $N+6$ | Yes | 68, m | MCI | 4 | Parietal, temporal | Left hemianopia, 20° | −/+ | −/+ | 25 |
| $N+7$ | Yes | 39, m | MCI | 5 | Parietal, temporal | Normal | −/+ | −/+ | 35 |
| $N+8$ | Yes | 45, f | MCI | 9 | Frontal, temporal | Normal | −/+ | −/+ | 11 |
| $N+9$ | Yes | 50, m | MCI | 2 | Temporal | Normal | −/+ | −/+ | 8 |
| Mean | | 54.2 years | | 4.9 (2–9) | | 5/9 impaired | 9 impaired | 8 impaired | 19.1% |
| B: Right brain damaged patients without visual neglect | | | | | | | | | |
| $N-1$ | No | 29, f | MCI | 1 | Temporal | Normal | +/+ | +/+ | 0 |
| $N-2$ | No | 62, f | MCI | 4 | Frontal, parietal | Normal | +/+ | +/+ | 1 |
| $N-3$ | No | 44, m | MCI | 6 | Temporal | Normal | +/+ | +/+ | 0 |
| $N-4$ | No | 62, m | MCI | 3 | Temporal, basal ganglia | Left hemianopia, 5° | +/+ | +/+ | 0 |
| $N-5$ | No | 57, f | MCI | 12 | Parietal, occipital | Normal | +/+ | +/+ | 1 |
| $N-6$ | No | 50, f | MCI | 4 | Parietal, occipital | Left hemianopia, 20° | +/+ | +/+ | 0 |
| $N-7$ | No | 62, m | MCI | 4 | Temporal | Left hemianopia, 4° | +/+ | +/+ | 1 |
| Mean | | | 52.2 years | 4.8 (1–12) | | 3/7 impaired | 0 impaired | 0 impaired | 0.1% |

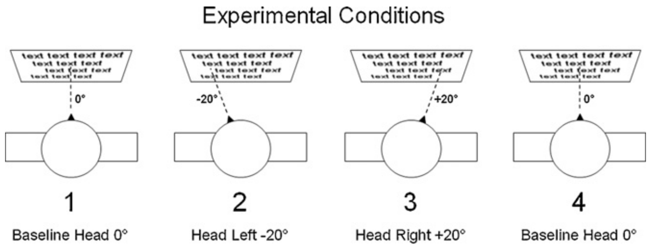


**Fig. 1.** Illustration of the four experimental conditions (see text for details). The rectangles indicate the subject's trunk, the circle the subject's head, and the black triangle the subject's nose. The head orientation is indicated by the stippled lines.

The testing room was dark and quiet to minimize distraction and the influence of other visual or auditory cues on reading. The observer distance was 0.5 m (from the subject's eyes to the monitor surface) in all experimental conditions, with all subjects wearing corrective glasses if necessary. After each reading text a blank screen was presented and a short break of 1–2 min was given to the subject. The whole experiment included frequent breaks and did not last longer than 30 min to reduce fatigue effects. To counter effects of spontaneous recovery all investigations were completed within 3 days in all patients, and within one session in the normal subjects.

### 2.5. Scoring of reading errors

The following two types of neglect-related reading errors were scored: (1) omissions of single words (each omitted word counted as 1 error). Completely omitted lines of text were not scored because they might represent a qualitatively different category of errors more related to oculomotor disorders (i.e. resulting from the left-sided field defect and/or saccadic disturbances) than to reading processes per se. (2) Word-based errors (errors on the left or right side of single words): these included omissions of leftsided letter(s), syllable(s) or half of a *single* word in compound words (i.e. keeper instead of housekeeper) and part-word substitutions, when letter(s), syllable(s) or half of a word was substituted (i.e. house instead of mouse). Whole-word substitutions were also excluded from the analysis as they might represent a qualitatively different category of reading problem that is not related to neglect. Appendixes A and B show an example of a representative patient with ND.

### 2.6. Data analysis

Data analyses were computed with SPSS, version 17. As there were ceiling effects in the RBD-control and the normal control group (see Sections 3.1 and 3.2 below), only the data of the neglect group were examined in analyses of variance for repeated measures (ANOVA). The dependent variables omission of words and word-based errors were calculated as relative errors (reading-errors divided by the *number of read words*). Note that for the calculation of relative word based errors the omitted words were not counted. Greenhouse–Geisser corrections of degrees of freedom were applied if appropriate.

A Wilcoxon Ranks Test was computed to compare the change of relative reading errors across the experimental conditions. Therefore, the relative change of reading errors in each condition was calculated as first baseline (errors) minus head turned to the left side (errors) and this result was divided by the number of reading errors in the first baseline. This calculation was made to control for the differences in error frequency between word-based and space-based errors. The adopted level of significance was 5%.

## 3. Results

### 3.1. Distribution of errors in paragraph reading

Within the neglect patient group omissions accounted for 90.2% of all reading errors in ND, whereas word-based errors accounted for 9.8% of the errors. Omissions in the ND group showed a clear left–right-gradient, being significantly more frequent on the contra- as ipsilesional side of the text in the first baseline (56.4% vs. 15.8%). The same left–right-gradient was found within the category of the word-based reading errors (6.9% leftsided vs. 0.9% rightsided omissions *within* the word).

Although we excluded completely omitted lines during reading in the neglect group from our analysis (see Section 2.5, above), it may be qualitatively interesting to note that they accounted for only 1.8% of total errors and occurred in two neglect patients only. Finally, whole-word substitutions – which we also excluded from our analysis (see Section 2.5, above) – accounted for only 0.2% of all errors in paragraph reading.

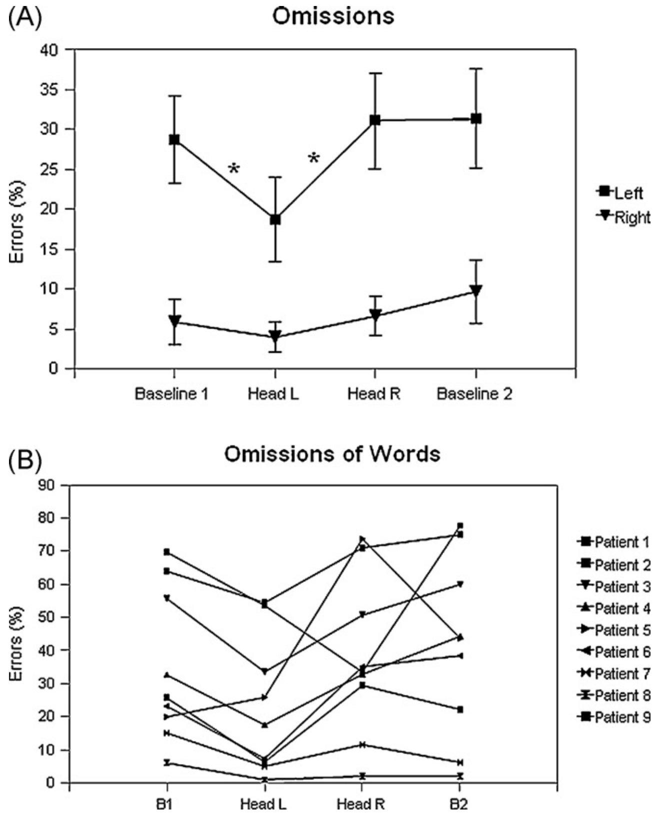


**Fig. 2.** (A) Mean percentage of spaced-based omission errors on the left and the right side of the text in the neglect patient group across the four experimental conditions. Error bars indicate standard error of the mean (SEM). The results of the two other subject groups (RBD patients without neglect and healthy control subjects) are not shown due to a floor effect in performance (<1% errors in any task). (B) Individual error percentages for left-sided omissions of the 9 neglect patients across all experimental conditions. Note that 8 out of 9 patients show a reduction of omissions selectively during left-ward head rotation in comparison to Baseline 1.

### 3.2. Omission of words

As only the neglect patient group committed a significant number of reading errors while the two non-neglect samples performed nearly errorless (see Appendix C for a survey of the mean number of omissions and word-based-errors) we limited the ANOVAs reported here and in Section 3.2 to the neglect patient group. The dependent variable omission of words was examined in an ANOVA with the within-subject factors Head Orientation (left, central, right) and Word Position (words presented in right or left hemispace). The main effects of Head Orientation [$F(1.62, 12.92) = 4.78$; $p = 0.034$], Error Position [$F(1, 8) = 31.17$, $p = 0.001$] and the Head Orientation × Error Position interaction [$F(3, 24) = 4.36$; $p = 0.014$] were significant.

Pairwise comparisons showed significant differences between Head Position left (Head Left) and all other head positions (Baseline 1; $p = 0.003$, Head Right; $p = 0.015$, Baseline 2; $p = 0.002$) for left sided omissions of whole words. Other comparisons (Baseline 1–Baseline 2, Head Right–Baseline 1; Head Right–Baseline 2) were not significant ($p > 0.27$ for each comparison). For the right text side, only the comparison between Head Left and Baseline 2 was significant ($p = 0.023$). Fig. 2 summarizes the results.

In addition to presenting group data (Fig. 2A) we present individual data of all neglect patients for leftward omission errors across all experimental conditions.

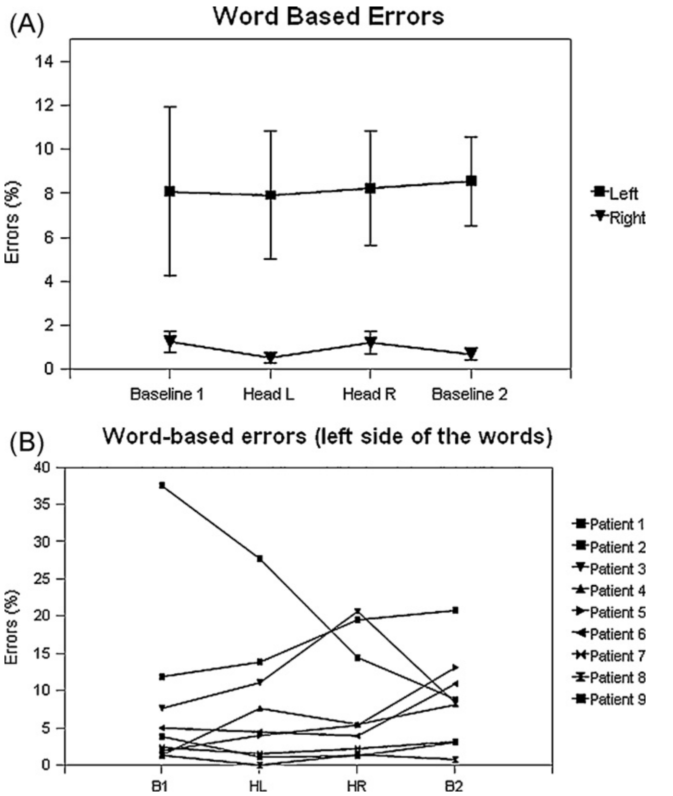


**Fig. 3.** (A) Mean percentage of word based reading errors on the left and the right side of single words in the neglect patient group across the four experimental conditions. The results of the two other subject groups (RBD patients without neglect and healthy control subjects) are not shown due to a floor effect in performance (<1% errors in any task). Note the different scaling of the $y$-axis in comparison to Fig. 2. Error bars indicate SEM. (B) Individual error percentages for word-based errors on the left side of words of the 9 neglect patients across all experimental conditions. Note that 8 out of 9 patients show no reduction of word-based errors during left- nor rightward head rotation in comparison to Baseline 1. Rather, a (non-significant) deterioration of performance is seen in Baseline 1 as compared to the other experimental conditions. Subject 2 showed a continuous reduction in word-based errors across all conditions and showed fewer errors in Baseline 2 vs. Baseline 1.

### 3.3. *Word-based reading errors*

Word based errors were examined in an ANOVA (which included only the neglect patient group, see Section 3.1, above) with the within-subject factor Head Orientation and Error Position (errors on the left or the right side of the word). The main effects of Head Orientation [$F(1.64, 13.14) = 4.89$; $p = 0.68$] and the Head Orientation × Error Position interaction [$F(3, 24) = 0.41$; $p = 0.74$] were not significant. Only the main effect of Error Position [$F(1, 8) = 16{,}74$; $p = 0.003$] was significant, showing that the neglect patients made more errors on the left side of the word (see Fig. 3).

In addition, we list individual error rates for omissions and word-based errors of every neglect patient and mean errors of the two nonneglecting samples in Appendix C. This shows that *each* of the 9 neglect patients committed more such leftsided word-based errors than both nonneglecting samples.

In addition to presenting group data (Fig. 3A) we present individual data of all neglect patients for leftward omission errors across all experimental conditions.

### 3.4. *Word-based errors compared with omission errors*

Here, we directly compared the modulatory effect of leftward HR in comparison to the first baseline on omissions and word-based reading errors. An ANOVA with the within-subject factors Head Orientation, Error Type (word-based error or spaced based error) and Error-Position (left or right side of the text or word) was computed. The main effects of Head Orientation [$F(3, 24) = 3.59$; $p = 0.028$], Error Type [$F(1, 8) = 22.47$; $p = 0.001$], Error Position [$F(1, 8) = 26.08$; $p = 0.001$] and the interactions (Head Orientation × Error Type [$F(3, 24) = 3.39$; $p = 0.034$] and Error Type × Error Position [$F(1, 8) = 17.89$; $p = 0.003$]) were significant. The interactions Head Orientation × Error Type × Error Position [$F(2.09, 16.78) = 2.31$; $p = 0.13$] and Head Orientation × Error Position [$F(1.43, 11.51) = 1.62$; $p = 0.23$] were not significant.

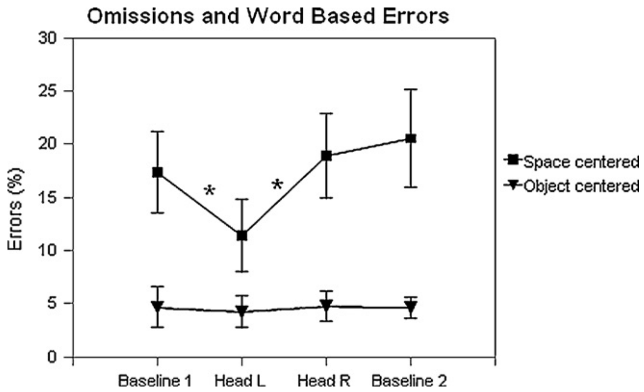


**Fig. 4.** Mean percentage of omissions and word based reading errors in the neglect group across the four experimental conditions. Error bars indicate SEM.

To examine whether HR affected the error types (word based vs. space based/omission errors) in a differential way, we examined the Head Orientation × Error-Type interaction more closely with pairwise comparisons. There were differences between Head Position left (Head Left) and all other head positions (Baseline 1; $p = 0.003$, Head Right; $p = 0.043$, Baseline 2; $p = 0.001$) *only* for omission errors. In contrast there was no significant effect of Head Orientation on word-based errors (all $ps > 0.53$).

A nonparametric (Wilcoxon Ranks) test was run to compare the change of error percentages (Head Left in relation to the first baseline) between the two error types (word-based and spaced-based/omission errors). The significant difference between the error types ($Z = -2.66$, $p = 0.008$) indicates that the reduction of space based errors (omissions) induced by HR was significantly higher than the reduction of word-based errors by leftward HR. Remember that we already showed in Section 3.2 (see above) that there was no significant difference in the frequency of word-based errors across the four experimental conditions in the neglect group. Together, these analyses underline the result that leftward HR significantly reduced omissions but not word-based reading errors in neglect. Fig. 4 summarizes the results of the neglect group when the two types of reading errors are considered independently of the side on which they occurred.

### 3.5. *Individual analyses of reading errors*

Finally, we evaluated whether the lack of any statistical effect of HR on word-based reading errors in our study might simply result from a lack of statistical power if only a minority of neglect patients in our sample actually might have shown such errors. Appendix C lists both types of reading errors (omissions and word-based errors) *individually* in every neglect patient in comparison to the minimum, maximum, and mean values of the two non-neglecting subject groups for the first baseline examination. As is evident from inspection of Appendix C, *every* neglect patient showed *both* types of reading errors. Second, although omission errors were more prominent than word-based errors in most of the patients, *every* neglect patient showed a higher rate of word-based errors in comparison to the mean error rates found in the

RBD-group without neglect and the healthy control group. These word-based errors are considered by some theorists as the "true" neglect dyslexia errors. Put differently: the lack of a statistically significant modulation of word-based errors by HR in the neglect group neither resulted from a scarcity of such errors nor from the theoretical possibility that only a minority of our neglect patients might have shown such word-based errors. In fact, none of the neglect patients performed normally with respect of word-based errors and therefore showed no ceiling-effect like the two non-neglecting subject groups. Hence, they could have improved their performance with respect to word-based errors significantly due to leftward HR but this did not occur. Appendixes A and B neatly illustrate this fact in a representative neglect patient: while leftward HR significantly reduced leftsided and in part also rightsided omissions the number of word-based errors (four) was identical during the baseline (straight head position, Appendix A) and during leftward HR (Appendix B). As no text was read twice during the experiments these word-based errors shown in Appendix B do not symbolize perseverations from a previously read text reading but stand for a specific problem in identifying the initial (hence leftsided) letters or syllables of words correctly in paragraph reading.

## 4. Discussion

Several findings are apparent from our study:

(i) Passive HR to the left, contralesional hemispace in the ND group significantly reduced omissions in the left hemispace and also in the right hemispace in comparison with Baseline 2. None of these results can be explained by learning effects or adaptation to testing procedures as the first and final baseline reading tests with a straight head position showed comparable performance in all subjects groups.

(ii) In contrast to the strong effect of HR on contralesional omissions, HR failed to influence word-based reading errors significantly. This non-effect was not due to a scarcity of word-based errors (some 8% of leftsided errors within single words were found in the neglect group vs. <1% errors in the two other samples). Furthermore this null-effect did not result from a lack of statistical power in the total neglect group as would have been the case if only a few patients had shown word-based reading errors. In fact, *all* 9 neglect patients showed omissions *and* word-based errors that were in *every* case more frequent than in any other person of the two nonneglecting samples (see Appendix C).

(iii) Omissions showed a clear left–right gradient in their frequency being more frequent on the contralesional vs. ipsilesional side. No hemispace difference was found for word-based reading errors but a clear left–right gradient was found with respect to the side of the errors *within* single words.

In the following we will discuss these findings and relate them to current theories of neglect and ND.

### *4.1. Egocentric mechanisms affect omissions in paragraph reading in neglect*

HR had a powerful influence on omissions in ND, as can be seen from the significant reduction of nearly 35% in left hemispace when compared with the first baseline. The improvement in right hemispace was comparable (33% reduction) but it was only significant in comparison with the second baseline where the patients committed slightly more omissions than in the first baseline. These results corroborate previous findings which showed significant modulatory effects of head- and trunk-position on numerous neglect phenomena (for review see Chokron et al., 2007; Kerkhoff, 2001). The improvements of ND in right hemispace – though not significant in comparison to Baseline 1 – may result from two factors. First, ND was so severe in some patients, that they read only some 40–50% in right hemispace. In such cases HR may significantly improve performance in *both* hemispaces when we assume that their egocentric reference is shifted markedly to the ipsilesional side. In addition or alternatively, HR may have improved ND in right hemispace by activating nonlateralized attentional mechanisms which in turn might have improved ND in ipsilesional hemispace. Given the fact that HR is likely to influence neuronal functioning in parietal cortex (Duhamel, Bremmer, Benhamed, & Graf, 1997) and that human parietal cortex is also concerned with *nonlateralized* spatial attentional mechanisms (Husain & Rorden, 2003) it might be expected that contralesional HR could act on such mechanisms thereby leading to improvements of ND in ipsilesional hemispace. This hypothesis might be tested empirically in subsequent studies. Together, our present results extend the earlier findings mentioned above to paragraph reading in ND thus corroborating the importance of the head saggitale as one important physical "anchor" for spatial orientation on the page during paragraph reading. A contralesional, passive rotation of this body part shifts the egocentric reference towards the neglected hemispace which in turn reduces leftsided omission in ND. Animal studies support the view that the monkey parietal cortex is crucially involved in such egocentric computations as shown by the significant modulation of neural activity induced by manipulations of eye-, head- or trunk-position as obtained from single-cell recordings in parietal neurons (Andersen, Snyder, Bradley, & Xing, 1997; Brotchie, Andersen, Snyder, & Goodman, 1995; Duhamel et al., 1997). Functional imaging and human patient studies also corroborate this view and highlight the importance of the fronto-parietal network for egocentric spatial processes (Hillis et al., 2005; Vallar et al., 1999).

Interestingly, rightward HR did not significantly aggravate the deficit in the neglect dyslexics as compared to a straight head position. This finding mirrors several previous findings in related studies (Karnath et al., 1991; Schindler & Kerkhoff, 1997), who both found no further deteriorating effect of rightward HR as compared to straight HR in neglect patients. The most likely explanation for this finding is that performance in many neglect patients with severe ND was already maximally deviated to the right, ipsilesional side in the straight head position, so that no further deterioration was possible with rightward HR. This was obviously the case in 5 out of 9 neglect patients from our sample who omitted more than 75% of the text in the left half of the presented reading tasks.

In summary, the head sagittale makes an important contribution to the egocentric reference in ND thus influencing the occurrence of omission errors during paragraph reading. This has implications for the treatment of deficits in paragraph reading because it appears likely that manipulations of the egocentric reference (via head- or trunk rotation) or via sensory stimulation (neck–muscle vibration, optokinetic stimulation, etc.) will influence omissions in paragraph or text reading in ND. In fact omissions in text reading can be significantly reduced with such methods (Chokron et al., 2007; Kerkhoff et al., 2006; Schindler, Kerkhoff, Karnath, Keller, & Goldenberg, 2002) while word-based errors during text reading remain unchanged after optokinetic stimulation therapy (Kerkhoff et al., 2006). Hence, alternative, novel treatments may be required in order to treat word-based reading errors in ND.

### *4.2. Egocentric mechanisms and word-based errors in paragraph reading in ND*

In contrast to the strong effect of HR on omissions in ND a null-effect of the same manipulation was obtained in the same reading tasks for word-based errors. Theoretically HR could have influenced the frequency of word-based errors in our neglect sample in both directions (i.e. increased it during rightward HR or decreased it during leftward HR), but no such effect was induced. Rather, the manipulation of the egocentric reference seemed to be irrelevant for the occurrence of word-based errors. In contrast to this null-effect a previous study (Schindler & Kerkhoff, 1997) investigating reading of centrally presented *single* words in neglect patients showed significant positive effects of leftward head- or trunk-rotation to the neglected hemispace. It is important to note, that in this previous study exactly the same manipulation of head position by 20° to the left or right side was adopted in an even smaller patient sample ($N = 5$). How can these two findings be reconciled? A related study by Behrmann and Tipper (1999) showed in a sophisticated experimental setup that contralesional neglect may co-exist simultaneously in a space- and an object-based reference frame with different degrees of severity. Interestingly, these authors also noted that the degree of contralesional neglect in both frames of reference was influenced by task contingencies and attentional strategies, and that the object-based spatial representation in their experimental setup was somewhat weaker (p. 85). A parsimonious explanation of our present results and those of Schindler and Kerkhoff (1997) in light of the findings by Behrmann and Tipper (1999) may therefore be, that ND in text reading expresses itself in at least two distinct reference fames – at the level of the whole text (global level) and at the level of single words (local level). In single word reading the global level and the local level are identical (both are determined by the word) and the two reference frames (space- vs. object-based are completely aligned). We therefore assume here, that HR is likely to affect primarily the *global* level (text in paragraph reading and single words in word reading), but fails to influence the *local* level (word identification during paragraph reading). It will be interesting to test in subsequent studies whether this represents a "fixed" mechanisms related to HR or whether specific task instructions inducing either a more global or a more local task strategy during reading are capable of manipulating the degree of ND in space- vs. word-based errors.

An alternative, not necessary excluding hypothesis for the non-modulation of word-based errors in paragraph reading in our study might be that such word-related information is not processed primarily in the *dorsal* visual stream which is more devoted to egocentric spatial processing (Hillis et al., 2005; Vallar et al., 1999). Instead, "object-like" visual information which might convey important clues to the length of a word may be preferentially processed in cortical areas of the ventral visual stream (i.e. occipito-temporal cortex). Lesions to such areas in the right hemisphere give rise to contralesional deficits in visual search for object-like forms (Grimsen et al., 2008; Ptak & Valenza, 2005) and word-based reading errors in ND (Lee et al., 2009). HR may thus activate mainly parietal cortex in our patients which in turn leads to improvements in omissions but not in word-based errors as this latter error type may be preferentially processed in ventral stream areas which however are not influenced by head rotation.

Finally, another account of our results may be that our word-based reading errors are not to be considered as "true" object-centered neglect errors but rather as an indication of "relative egocentric neglect" (Driver & Pouget, 2000). These authors have argued that many claims of pure "object"- or allocentric neglect phenomena in fact can all be explained in purely egocentric terms, provided that relative egocentric position matters in addition to absolute egocentric position. In fact the dysfunctional eye fixation pattern reported in one ND study (Behrmann et al., 2002) according to which the lack of proper fixation of the word beginning is tightly coupled with incorrect reading of this word would fit to this account. Fixating single words more on the right, ipsilesional side of words would exactly create such a *relative* egocentric neglect pattern where letters to the left of the landing position of the saccade on the word during reading would be incorrectly processed thus leading to word-based errors. However, regardless of whether we conceive word-based errors as an expression of object-centric or relative egocentric neglect the non-modulation of such errors by HR in paragraph reading is an interesting phenomenon which requires further study.

### 4.3. Error analysis in paragraph reading in ND

As stated above, omission errors accounted for the great majority of all errors committed during text reading in the neglect dyslexics and showed a clear left–right gradient in their frequency. This is comparable to similar left–right gradients of performance in visual search or cancellation tasks in patients with visual neglect (for review see Kerkhoff, 2001). The non-spatial relationship of word-based reading errors in ND – hence their comparable frequency on both sides of the page – is in accordance with the results of studies on object-centered visual neglect, which have demonstrated that object-centered perception operates independently of the hemispace where the stimulus is presented in Humphreys and Riddoch (1995). In line with the findings that egocentric visual neglect in a cancellation task was much more frequent than allocentric (object-centered) visual neglect in the same task (Hillis et al., 2005) we also found that omissions were more frequent than word-based reading errors during paragraph reading in ND.

## 5. Conclusions

In conclusion, the present study clearly demonstrates the dissociative, highly specific effects of HR on reading performance in a paragraph reading in ND. The egocentric manipulation used here effectively influenced omissions but not word-based errors which has implications for theory and treatment of ND. On a theoretical level, the results confirm the independence of these two types of errors and suggest the dissociability of the underlying attentional processes. With respect to the treatment of ND it follows from our results that omissions can be cured with treatment approaches using manipulations of the egocentric reference (Chokron et al., 2007) while the less frequent but nevertheless relevant word-based reading errors probably require the development of alternate therapy approaches that specifically influence object-/word-centered attention in ND.

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## Appendixes A and B.

Example of the reading performance of a neglect dyslexic patient in the first baseline (A) and with head turned to the left (B). Omissions are outlined, word-based errors encircled.


## Appendix C.

Individual error data for left- vs. rightsided omissions (%) and left- vs. rightsided word-based reading errors (%) during the first baseline tests in the neglect patients (patient numbers correspond to those in Table 1). At the bottom of the table, the minimum, mean and maximum percentages of the Right-Brain-Damaged Control Group without neglect and the Normal control Group are indicated for comparison. Note that *every* neglect patient committed more omissions and more word-based errors than the worst subject (=max. error percentage) in any of the two nonneglecting control groups.

| Patient | Space-based errors | | Word-based errors | |
|---|---|---|---|---|
| | Left | Right | Left | Right |
| 1 | 23.73 | 1.94 | 3.82 | 0.00 |
| 2 | 43.50 | 26.23 | 37.50 | 0.00 |
| 3 | 42.51 | 13.22 | 7.63 | 0.69 |
| 4 | 32.12 | 0.50 | 1.35 | 0.00 |
| 5 | 17.52 | 2.46 | 1.91 | 0.47 |
| 6 | 22.85 | 0.37 | 4.99 | 1.36 |
| 7 | 15.09 | 0.00 | 2.36 | 1.80 |
| 8 | 4.83 | 1.22 | 1.30 | 3.89 |
| 9 | 57.00 | 7.00 | 11.88 | 3.13 |
| Controls | | | | |
| Mean RBD (min–max) | 0.17 (0–0.8) | 0.00 (0–0) | 0.34 (0–0.8) | 0.63 (0–1.6) |
| Mean normal (min–max) | 0.00 (0–0) | 0.00 (0–0) | 0.13 (0–0.4) | 0.07 (0–1.2) |

## References


Andersen, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual Review of Neuroscience*, *20*, 303–330.

Aulhorn, E., & Harms, J. (1972). Visual perimetry. In D. Jameson, & L. Hurvich (Eds.), *Handbook of sensory physiology* (pp. 102–145). Berlin: Springer.

Azouvi, P., Samuel, C., Louis-Dreyfus, A., Bernati, T., Bartolomeo, P., Beis, J. M., et al. (2002). Sensitivity of clinical and behavioural tests of spatial neglect after right hemisphere stroke. *Journal of Neurology Neurosurgery and Psychiatry*, *73*, 160–166.

Bachman, L., Fein, G., Davenport, L., & Price, L. (1993). The indented paragraph reading test in the assessment of left hemi-neglect. *Archives of Clinical Neuropsychology*, *8*, 485–496.

Behrmann, M., Black, S. E., McKeef, T. J., & Barton, J. J. S. (2002). Oculographic analysis of word reading in hemispatial neglect. *Physiology and Behavior*, *77*, 613–619.

Behrmann, M., Moscovith, M., Black, S. E., & Mozer, M. (1990). Perceptual and conceptual mechanisms in neglect dyslexia. *Brain*, *113*, 1163–1183.

Behrmann, M., & Tipper, S. P. (1999). Attention accesses multiple reference frames: Evidence from visual neglect. *Journal of Experimental Psychology-Human Perception and Performance*, *25*, 83–101.

Binder, J., Marshall, R., Lazar, R., Benjamin, J., & Mohr, J. P. (1992). Distinct syndromes of hemineglect. *Archives of Neurology*, *49*, 1187–1194.

Brotchie, P. R., Andersen, R. A., Snyder, L. H., & Goodman, S. J. (1995). Head position signals used by parietal neurons to encode locations of visual stimuli. *Nature*, *375*, 232–235.

Caplan, B. (1987). Assessment of unilateral neglect: A new reading test. *Journal of Clinical and Experimental Neuropsychology*, *9*, 359–364.

Caramazza, A., & Hillis, A. E. (1990). Spatial representation of words in the brain implied by studies of a unilateral neglect patient. *Nature*, *346*, 267–269.

Chokron, S., Dupierrix, E., Tabert, M., & Bartolomeo, P. (2007). Experimental remission of unilateral spatial neglect. *Neuropsychologia*, *45*, 3127–3148.

Driver, J., & Pouget, A. (2000). Object-centered visual neglect, or relative egocentric neglect? *Journal of Cognitive Neuroscience*, *12*, 542–545.

Duhamel, J. R., Bremmer, F., Benhamed, S., & Graf, W. (1997). Spatial invariance of visual receptive fields in parietal cortex neurons. *Nature*, *389*, 845–848.

Ellis, A. W., Flude, B. M., & Young, A. W. (1987). "Neglect dyslexia" and the early visual processing of letters in words and non-words. *Cognitive Neuropsychology*, *4*, 439–464.

Grimsen, C., Hildebrandt, H., & Fahle, M. (2008). Dissociation of egocentric and allocentric coding of space in visual search after right middle cerebral artery stroke. *Neuropsychologia*, *46*, 902–914.

Halligan, P. W., Fink, G. R., Marshall, J. C., & Vallar, G. (2003). Spatial cognition: Evidence from visual neglect. *Trends in Cognitive Sciences*, *7*, 125–133.

Halligan, P. W., Marshall, J. C., & Wade, D. T. (1989). Visuospatial neglect: Underlying factors and test sensitivity. *Lancet*, *2*, 908–911.

Haywood, M., & Coltheart, M. (2001). Neglect dyslexia with a stimulus-centered deficit and without visuospatial neglect. *Cognitive Neuropsychology*, *18*, 577–615.

Hillis, A. E., Newhart, M., Heidler, J., Barker, P. B., Herskovits, E. H., & Degaonkar, M. (2005). Anatomy of spatial attention: Insights from perfusion imaging and hemispatial neglect in acute stroke. *The Journal of Neuroscience*, *25*, 3161–3167.

Honda, M., Wise, S. P., Weeks, R. A., Deiber, M.-P., & Hallett, M. (1999). Cortical areas with enhanced activation during object-centred spatial information processing. A PET study. *Brain*, *121*, 2145–2158.

Humphreys, G. W., & Riddoch, M. J. (1995). Separate coding of space within and between perceptual objects: Evidence from unilateral visual neglect. *Cognitive Neuropsychology*, *12*, 283–311.

Husain, M., & Rorden, C. (2003). Non-spatially lateralized mechanisms in hemispatial neglect. *Nature Reviews. Neuroscience*, *4*, 26–36.

Karnath, H. O., Schenkel, P., & Fischer, B. (1991). Trunk orientation as the determining factor of the 'contralateral' deficit in the neglect syndrome and as the physical anchor of the internal representation of body orientation in space. *Brain*, *114*, 1997–2014.

Kerkhoff, G. (2001). Hemispatial neglect in man. *Progress in Neurobiology*, *63*, 1–27.

Kerkhoff, G. (2003). Transient modulation and rehabilitation of spatial neglect by sensory stimulation. *Progress in Brain Research*, *142*, 257–281.

Kerkhoff, G., Keller, I., Ritter, V., & Marquardt, C. (2006). Repetitive optokinetic stimulation with active tracking induces lasting recovery from visual neglect. *Restorative Neurology and Neuroscience*, *24*, 357–370.

Kerkhoff, G., Münβinger, U., Eberle-Strauss, G., & Stögerer, E. (1992). Rehabilitation of hemianopic alexia in patients with postgeniculate visual field disorders. *Neuropsychological Rehabilitation*, *2*, 21–42.

Ladavas, E., Umilta, C., & Mapelli, D. (1997). Lexical and semantic processing in the absence of word reading: Evidence from neglect dyslexia. *Neuropsychologia*, *35*(8), 1075–1085.

Lee, B. H., Suh, M. K., Kim, E.-J., Seo, S. W., Choi, K. M., Kim, G.-M., et al. (2009). Neglect dyslexia: Frequency, association with other hemispatial neglects, and lesion localization. *Neuropsychologia*, *47*, 704–710.

Ptak, R., & Valenza, N. (2005). The inferior temporal lobe mediates distracter-resistant visual search of patients with spatial neglect. *Journal of Cognitive Neuroscience*, *17*, 788–799.

Riddoch, J. (1990). Neglect and the peripheral dyslexias. *Cognitive Neuropsychology*, *7*, 369–389.

Schindler, I., & Kerkhoff, G. (1997). Head and trunk orientation modulate visual neglect. *NeuroReport*, *8*, 2681–2685.

Schindler, I., & Kerkhoff, G. (2004). Convergent and divergent effects of neck proprioceptive and visual motion stimulation on visual space processing in neglect. *Neuropsychologia*, *42*, 1149–1155.

Schindler, I., Kerkhoff, G., Karnath, H.-O., Keller, I., & Goldenberg, G. (2002). Neck muscle vibration induces lasting recovery in spatial neglect. *Journal of Neurology, Neurosurgery, and Psychiatry*, *73*, 412–419.

Stenneken, P., van, E. L., Keller, I., Jacobs, A. M., & Kerkhoff, G. (2008). Task-dependent modulation of neglect dyslexia? Novel evidence from the viewing position effect. *Brain Research*, *1189*, 166–178.

Towle, D., & Lincoln, N. B. (1991). Use of the indented paragraph test with right hemisphere-damaged stroke patients. *British Journal of Clinical Psychology*, *30*, 37–45.

Vallar, G., Lobel, E., Galati, G., Berthoz, A., Pizzamiglio, L., & Le Bihan, D. (1999). A frontoparietal system for computing the egocentric spatial frame of reference in humans. *Experimental Brain Research*, *124*, 281–286.

Ventre, J., & Flandrin, J. M. J. M. (1984). In search for the egocentric reference. A neurophysiological hypothesis. *Neuropsychologia*, *22*, 893–906.

Verdon, V., Schwartz, S., Lovblad, K. O., Hauert, C. A., & Vuilleumier, P. (2010). Neuroanatomy of hemispatial neglect and its functional components: A study using voxel-based lesion-symptom mapping. *Brain*, *133*, 880–894.

Wilson, B., Cockburn, J., & Halligan, P. (1987). Development of a behavioral test of visuospatial neglect. *Archives of Physical Medicine and Rehabilitation*, *68*, 98–102.