INTRODUCTION

Reading is a complex cultural skill that is supported by various visual, spatial, phonological, orthographic, and semantic processes. Any of these processing levels can be impaired independently of the other levels and manifest as specific reading impairment. Neglect dyslexia is a peripheral reading disorder (i.e., affects the visual-perceptive, or attentional stages of reading) that occurs mostly in the context of spatial neglect following right-hemispheric perisylvian damage (Ellis, Flude, & Young, 1987; Riddoch, Humphreys, Cleton, & Fery, 1990; Vallar, Burani, & Arduino, 2010). Patients with neglect dyslexia omit or substitute the initial letters of a word, which may lead to productions that are partly visually similar with the target word, but bear no semantic connection with it (e.g., “pillow” for YELLOW, or “hair” for CHAIR). About one half of all patients with neglect dyslexia also have a left-sided visual field defect such as hemianopia (Lee et al., 2009; Ptak, Di Pietro, & Schneider, 2012), but cases with opposite impairments have been described (e.g., right visual field impairment with left neglect dyslexia; Arduino, Daini and Silveri, 2005; Ptak, Di Pietro, & Pignat, 2016), indicating that hemianopia is not the main explanatory factor of neglect dyslexia.

Spatial neglect is a stronger predictor of neglect dyslexia than hemianopia. In one study (Lee et al., 2009), out of 138 right-hemisphere damaged patients, 80 (58%) had spatial neglect, and 30 out of these (37.5%) also had neglect dyslexia. Another study found neglect dyslexia in 19 out of 40 (47.5%) neglect patients (Ptak et al., 2012). However, while there is a strong relation between neglect dyslexia and neglect assessed with classic tests (cancellation, line bisection, drawing, etc.), some patients with neglect dyslexia do not exhibit signs of neglect on these tests (Haywood & Coltheart, 2001; Miceli & Capasso, 2001). This finding suggests that single-word reading depends on a distinct frame of reference, which is independent of reference frames involved in spatial exploration (Hillis, 2006). Based on a thorough analysis of reading patterns of neglect patients, Hillis and Caramazza (1995) made the distinction between viewer-centered, stimulus-centered, and object-centered deficits. They emphasized that in standard print patients with all forms of neglect make errors on the word beginning. In contrast, viewer-centered errors vary in function of the horizontal retinal position of the stimulus, while stimulus-centered errors remain relatively stable for words presented centrally, or in the left or right hemifield. The least common form is the object-centered reference frame, which is characterized by reading errors to the word beginning or end irrespective of reading direction (horizontal from left to right and right to left, or vertical). Interestingly, among classic neglect tests, line bisection correlates particularly strongly with the degree of neglect dyslexia (Azouvi et al., 2002; Lee et al., 2009; Ptak et al., 2012), suggesting that reading and line bisection may share a common reference frame. Anatomical findings support this observation, indicating that neglect in reading and line bisection is associated with more posterior damage involving the parietal, temporal, and occipital cortex (Binder, Marshall, Lazar, Benhamin and Mohr, 1992, Chechlacz et al., 2010; Golay, Schnider, & Ptak, 2008; Medina et al., 2009), while spatial exploration deficits result from damage of perisylvian and lateral frontal cortex (Karnath & Rorden, 2012; Molenberghs, Sale, & Mattingley, 2012). In agreement with these findings, a recent study on a large population of right-hemisphere damaged patients showed that reading and line bisection are associated with a latent factor distinct from—though closely associated with—the factor predicting cancellation deficits (Pedrizzini, Schnider, & Ptak, 2017).

Most previous intervention studies targeted neglect defined as deficit of spatial attention and exploration (Kerkhoff & Schenk, 2012), but did not specifically measure improvements in single-word reading (see Daini et al., 2013; and Reinhart, Schindler, & Kerkhoff, 2011; for an exception using optokinetic stimulation). However, several studies used
reading measures to evaluate the effect of different interventions on neglect symptoms. Prism adaptation (PA) with right-deviating prisms is a technique whose benefits for neglect recovery have been widely debated, since several studies supported partial restoration of neglect following repeated PA (Frassinetti, Angeli, Meneghello, Avanzi, & Ladavas, 2002; Ladavas, Bonifazi, Catena and Serino, 2011, Mizuno et al., 2011; Rossetti et al., 1998; Saevassson, Kristjansson, Hildebrandt and Halsband, 2009, Serino, Barbiani, Rinaldesi, & Ladavas, 2009), while other studies reported similar efficacy as other methods (Priftis, Passarini, Pilosio, Meneghello, & Pitteri, 2013), mixed results (Nys, de Haan, Kunneman, de Kort, & Dijkerman, 2008), or absence of positive effects (Rousseaux, Bernati, Saj, & Kozlowski, 2006; Turton, O’Leary, Gabbi, Woodward, & Gilchrist, 2010). The basic principle of PA is that all that the observer sees through the goggles is shifted relative to his body midline. As a consequence, when asked to point to an object the observer directs his hand toward the perceived position of the object, and after noticing the error, performs a corrective movement in the opposite direction. After several pointing movements, the correction is implemented already at the beginning of the movement. The systematic bias induced by PA can be measured by asking the observer to take away the goggles, fixate an object in front, and point to this object with closed eyes. Adapted pointing movements are shifted opposite to the bias induced by the prismatic goggles.

The present study examined whether reading of single words in a patient showing a relatively pure form of neglect dyslexia could be improved using PA. The findings support previous observations suggesting that single-word reading does not benefit from the visuomotor aftereffect created by PA.

**Case report**

AB, a 66-year-old retired policeman, suffered from an ischemic stroke affecting the right posterior thalamus, occipital lobe, posterior hippocampus, and the splenium of the corpus callosum (Figure 1). At the initial neuropsychological examination 7 days following stroke, the patient presented a left-sided visual field loss on confrontation testing and spatial neglect on cancellation, drawing, and line bisection. These symptoms quickly receded, and AB could leave the hospital after a short rehabilitation phase. He continued to complain about a restriction of the left visual field, difficulties finding his way in new environments and reading problems. The patient underwent a neuropsychological examination of visual functions and reading, as well as a single PA session. Because an incomplete left superior quadrantanopia was observed at the initial digital confrontation testing, binocular campimetric testing was performed in the subacute phase. The patient was required to fixate a gray cross and to indicate the presence of a white dot (0.5 degrees) presented for 150 ms. The test was under control of the experimenter, who initiated presentation of the next stimulus only when the patient was fixating the central cross. Stimuli were shown on a black 20° screen, randomly on a grid of one degree cell size. This examination revealed a residual visual field defect in the upper left quadrant starting approximately at 10 degrees left of fixation and 6 degrees above the horizontal meridian (Figure 2). Note that all stimuli presented during the reading tests fell into the spared part of the visual field. The patient was independent in daily life except for occasional difficulties finding his way in new environments and impaired reading. The neuropsychological examination revealed preserved visual and spatial functions (in particular, no signs of spatial neglect and only slightly impaired detection of stimuli flashed to the left hemifield under single or double stimulation) except for horizontal size estimation as assessed with line bisection or position discrimination (Table 1). His estimation of the subjective midline on line bisection was slightly biased to the left, which is the opposite of what can be observed in patients with left spatial neglect. However, though significant the bias remained small and well below values that would be considered as clinically relevant (Ferber & Karnath, 2001).

Reading was assessed with single words pseudo-randomly dispersed on a sheet of paper (Ptak et al., 2012) and the reading test of the Behavioural Inattention Test, which contains three columns of text (Wilson, Cockburn, & Halligan, 1987). Single-word reading was slow and characterized by omissions of the beginning letters (e.g., “mestique” for DOMESTIQUE—domestic; “promettre” for COMPROMETTRE—compromise), indicative of neglect dyslexia. AB read 31 of 40 words correctly, though he was sometimes capable of correcting his error. In contrast, he did not make errors in text reading (possibly because this provided a better structured situation), but was very slow and slavishly followed each line.

The patient gave written informed consent to participate in this study, and the study was approved by the Ethical commission of the University Hospitals Geneva.

**Material and procedure**

Single-word reading before and after PA was examined with high-frequency (mean: 673 per million) words composed of 4, 6, 8, or 10 letters (New, Pallier, Brysbaert, & Ferrand, 2004).

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Figure 1. T2-weighted MRI scan showing right occipital (1), hippocampal and parahippocampal (2), internal capsule (3), splenial (4), and thalamic ischemia (5).
Four word lists were prepared, each containing 30 nouns of each length, for a total of 120 words. The average frequency of the four lists was closely matched and therefore statistically indistinguishable ($F(3, 476) = 0$, MSE = 3.9).

All items were presented centrally on a 17" large computer screen in white, capital 60-point Courier font on black background. AB was seated at a distance of approximately 60 cm from the screen and saw the stimuli at an approximate size of 1.5 degrees of visual angle. Each trial began with the presentation of a white fixation cross (2000 ms), immediately replaced by a stimulus word (150 ms, unmasked) and followed by a blank period until response of the patient. The experimenter noted the verbatim response of the patient for later analysis and released the next trial by clicking on the mouse. This procedure was repeated at four occasions: at baseline 1 week before PA, immediately before PA (pretest), immediately after PA (posttest) and 24 h after PA (late test).

PA was induced with prismatic goggles deviating by 15 degrees to the right and closely followed the procedure devised by Rossetti et al. (1998). While wearing the goggles AB was asked to perform 60 pointing movements toward two black dots located at arm length, 15 degrees to the left/right of the body midline. The patient’s head was supported by a chinrest to which a large shield made of cardboard was attached so as to hide most of the table from view (only the two target dots and approximately 5 cm of space in front of them were visible). Therefore, during adaptation the arm of the patient was hidden from view and he was only able to see the last part of his pointing movement (Ladavas et al., 2011). The degree of adaptation was measured with 10 pointing movements performed without goggles, by asking the patient to look at the dot indicated by the examiner, close his eyes, and touch the dot with his index finger.

**Results**

**Reading before PA**

Two methods were used to analyze reading errors of AB. For the first analysis neglect dylexia errors were defined as omissions, substitutions, or additions left to a clearly identifiable “neglect point” within a word (e.g., "lynx" instead of "SPHYNX, where the neglect point is before the letter Y, and which

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**Table 1. Neuropsychological scores of AB in visual-perceptual tests.**

| Test                                               | Optimal score | Patient score | Qualification |
|----------------------------------------------------|---------------|---------------|---------------|
| Visual object and space perception battery        |               |               |               |
| Incomplete letters                                 | 20            | 19            | Preserved     |
| Silhouettes                                        | 30            | 15            | Preserved     |
| Object decision                                    | 20            | 15            | Preserved     |
| Progressive silhouettes                            | 2             | 11            | Preserved     |
| Dot counting                                       | 10            | 8             | Preserved     |
| Position discrimination                            | 20            | 16            | Impaired      |
| Number location                                    | 10            | 10            | Preserved     |
| Cube analysis                                      | 10            | 10            | Preserved     |
| Birmingham Object Recognition Battery              |               |               |               |
| Length match                                       | 30            | 24            | Preserved     |
| Size match                                         | 30            | 24            | Preserved     |
| Montréal–Toulouse perception test                  |               |               |               |
| Identical figures                                  | 10            | 10            | Preserved     |
| Overlapping figures                                | 36            | 36            | Preserved     |
| Functional association match                       | 10            | 10            | Preserved     |
| Categorical association match                      | 10            | 10            | Preserved     |
| Extinction                                         |               |               |               |
| Left                                               | 24            | 20 (83%)      | Impaired      |
| Right                                              | 24            | 24 (100%)     | Preserved     |
| Bilateral                                          | 36            | 36 (83%)      | Impaired      |
| Behavioural Inattention Test                       | 146           | 142           | Preserved     |
| Line crossing                                      | 36            | 36            | Preserved     |
| Letter cancellation                                | 40            | 40            | Preserved     |
| Star cancellation                                  | 54            | 54            | Preserved     |
| Figure and shape copying                           | 4             | 4             | Preserved     |
| Line bisection                                     | 9             | 5             | Impaired      |
| Representational drawing                           | 3             | 3             | Preserved     |
| Line bisection, mean error in %                   | 0             | −4.53         | Impaired      |

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aWarrington and James (1991), bRiddoch and Humphreys (1993), cAgniel, Joanette, Doyon, and Duchêne (1992), dWilson et al. (1987), and eSchenkenberg, Bradford, and Ajax (1980).
would be counted as mixed omission/substitution error) (Ellis et al., 1987). For the second analysis errors were examined letter-wise, by checking for each letter whether it was subject to a substitution or omission error (Martelli, Arduino, & Daini, 2011). The latter analysis has the advantage that it also considers reading errors not classified as neglect dyslexia errors according to the approach of Ellis et al. (1987).

In the pretest, AB read only 12 of 120 words correctly (10%) and gave no answer for 18 (15%) other words. Reading errors were mostly omissions (17.5%; e.g., “orus” for CHORUS), substitutions (8.3%; e.g., “jonction” —junction for FRICTION) or a combination of omissions and substitutions (15%; e.g., “nuance” for REDONDANCE). Overall, 41.6% of all errors were classified as neglect dyslexia errors (i.e., errors clearly concerned the beginning of the word). 33.3% of all items errors did not respect the neglect dyslexia pattern, though most resembled the target word at least partly (e.g. “agent” for GADGET). Figure 3(a) shows the results of the letter-based analysis, which considered for every letter whether it was identified correctly, independently of how the reading error was classified. As the figure shows, AB’s performance was worse for initial letter positions and increased for letters toward the end of the word. This effect was found irrespective of word length, though overall performance was lower for longer compared to shorter words. We fitted a log-linear model on the four letters of each word length that occupied the same absolute spatial position in egocentric terms (e.g., the first letter of a four-letter word corresponded with the second letter of a six-letter word and the third letter of an eight-letter word, etc.). A model predicting only effects of word length (partial \( X^2 = 37.92, df = 3, p < .001 \)) and absolute letter position (partial \( X^2 = 60.48, df = 3, p < .001 \)) was the best fit to the data. In Figure 3(b) the scatter dots are aligned according to the position of letters within each word (i.e., the first letter of each word is shown on the first position). Again, a log-linear model with the main effects of word length (partial \( X^2 = 167.77, df = 3, p < .001 \)) and relative letter position was the best fit to the data (partial \( X^2 = 95.9, df = 3, p < .001 \)). Thus, the accuracy of AB when identifying individual letters embedded in words depended on two additive variables: the position of the letter and word length.

**PA aftereffect**

The average left/right deviation between 10 pointing movements and the dot was measured before PA, immediately after PA, and at the late test. The deviation was significantly greater after (−5.2 degrees) than before PA (−1.3 degrees; \( t(9) = 8.51, p < .0001 \)) and fell to baseline level after 24 h (−2 degrees; \( t(9) = 6.86, p < .0001 \)). Thus, AB successfully adapted to the deviating prisms, but the adaptation effect disappeared at the late test.

**Absence of effects of PA on reading**

Figure 4(a) shows the number of words read correctly at the four testing occasions, and Figure 4(b) presents the distribution of neglect dyslexia errors. Changes of performance before compared to after adaptation were examined using Chi-square tests. Concerning the number of items read correctly, there was no significant change between baseline and pretest (\( \chi^2 = 1.55, p = .21 \)), pretest and posttest (\( \chi^2 = 0.02, p = .88 \)) and between pretest and late test (\( \chi^2 = 0.02, p = .88 \)). Likewise, the frequency of neglect dyslexia errors did not differ between baseline and pretest (omission errors: \( \chi^2 = 0.29, p = .59 \); substitution errors: \( \chi^2 = 1.45, p = .23 \)); pretest and posttest (omission errors: \( \chi^2 = 1.62, p = .2 \)), pretest and posttest (omission: \( \chi^2 = 0.32, p = .57 \); substitution: \( \chi^2 = 0.08, p = .77 \)); pretest and posttest (omission: \( \chi^2 = 3.07, p = .08 \); substitution: \( \chi^2 = 0.2, p = .66 \)); pretest and posttest (omission: \( \chi^2 = 0.2, p = .65 \)).

Figure 5 shows the percentages of letter-based omission and substitution errors at the four time-points of testing. In order to evaluate whether PA had an effect on these letter-based errors,
we performed a log-linear analysis on the frequency of letter omissions and substitutions in function of the time of test and word length, but irrespective of letter position. This analysis only revealed a significant effect of word length (more errors for longer than shorter words; partial $\chi^2 = 2.820.48$, $df = 3$, $p < .0001$) and of error type (more omissions than substitutions; partial $\chi^2 = 2.053.1$, $df = 1$, $p < .0001$), but no effect of time of test (partial $\chi^2 = 5.61$, $df = 3$, $p = .13$), nor a significant interaction involving this variable.

**Discussion**

Neglect dyslexia mostly occurs in the context of spatial neglect, as evidenced in tasks such as cancellation, line bisection, drawing, and spatial exploration (Lee et al., 2009; Vallar et al., 2010). Patients with neglect dyslexia often have particularly severe neglect in these tasks, but also exhibit impairments of oculomotor behavior that is more important than the relatively subtle deficits of ocular scanning observed in
most neglect patients (Fellrath & Ptak, 2015; Primativo, Arduino, de Luca, Daini, & Martelli, 2013; Ptak, Golay, Müri, & Schneider, 2009). So far, rehabilitation studies attempted to treat neglect dyslexia in the context of the lateralized bias characterizing spatial neglect. For example, early studies attempted to facilitate spatial exploration during text reading using spatial cues presented at the beginning of each line and training patients to systematically identify these cues before reading a new line of text (Weinberg et al., 1977). Such training shows benefits for text reading, but may be less effective for the reading of strings of symbols (such as single words or long numbers). By using PA, Rossetti et al. (1998) found that patients showed significant improvement of neglect up to 2 h following a single, 5-min adaptation phase to rightward deviating prisms. Several controlled studies confirmed the beneficial effects of PA on global measures of neglect (Frassinetti et al., 2002; Serino et al., 2009), activities of daily living (Mizuno et al., 2011), eye movements (Angeli, Benassi, and Ladavas, 2004), auditory neglect (Jacquin-Courtois et al., 2010), mental imagery (Rode, Rossetti, & Boisson, 2001), or even postural imbalance (Tilikete et al., 2001). Contrasting with these previous observations, the present study shows that PA neither modified the frequency nor the distribution of reading errors of a patient with pure neglect dyslexia. This finding adds to several negative reports showing that PA does not always have positive effects on signs of spatial neglect, as measured with various classical neglect tests (Rousseaux et al., 2004; Turton et al., 2010).

Negative findings provide the opportunity to discuss the possible advantages and shortcomings of an intervention method, to identify critical experimental or patient variables and thus to propose therapies tailored to the specific needs of individual patients. However, such findings can be difficult to interpret, as one has to be sure that the intervention has been performed in accordance with previous positive studies. Fortunately, the adaptation effect induced by PA provides a straightforward measure of the success of PA. At posttest, the present patient showed a significant adaptation effect, which was lost 24 h later. The size of the adaptation effect was compatible with that in previous studies (e.g., 4.4 degrees measured by Angeli et al., 2004, 6 degrees measured by Ladavas et al., 2011). Therefore, if the adaptation effect had any impact on reading this should have been observed at the posttest. The adaptation procedure also closely resembled the procedure devised by Ladavas et al. (2011), who noted that the visibility of the arm during PA is a crucial factor for the transfer of PA effects on behavioral neglect measures. It is therefore unlikely that the PA procedure or the size of the PA aftereffect was responsible for the absence of effects in reading. Likewise, the fact that only a single adaptation session was performed cannot explain the absence of PA effects, as several previous studies reported significant transfer of PA aftereffects to cancellation, drawing, and even reading following one session of PA (Angeli et al., 2004; McIntosh, Rossetti, & Milner, 2002; Rossetti et al., 1998).

While disappointing, the absence of a positive effect of PA is in line with some studies that were unable to reproduce the positive results reported previously. For example, Morris et al. (2004) found no effect of PA on visual search in patients with neglect. In a group of 10 neglect patients, Rousseaux et al. (2006) failed to replicate effects of a single adaptation session (as measured with cancellation, line bisection, and scene drawing). These authors also examined single-word reading and did not find any positive impact of PA. Finally, Turton et al. (2010) performed a randomized-controlled study using repeated PA with 16 neglect patients as compared to 18 patients treated with “sham” (i.e., non-deviating) prisms. The authors found that both patient groups improved their performance in neglect tests across the study interval, but that improvement was comparable across groups and therefore was not attributable to PA but to spontaneous recovery or other factors.

The present results stand in particular contrast to the study of Angeli et al. (2004), who observed positive effects of a single PA session on word spelling in a group of eight neglect patients, and Farne, Rossetti, Tonio, and Ladavas (2002), who found positive effects in six patients. Specifically, Angeli et al.’s patients improved in single-word reading from 45% to 60%. The main difference between the patient tested in the present study and the patients of Angeli et al. (2004) and Farne et al. (2002) is that AB exhibited neglect dyslexia in the absence of other signs of spatial neglect in cancellation, line bisection, or other visuospatial tasks. Furthermore, while in the present study the patient’s reading performance was measured with accelerated presentation, in both previous studies the presentation time was not limited. AB may thus have had a lighter and more pure form of neglect dyslexia, and this may be the main reason for the absence of a PA effect on reading. Indeed, previous studies reporting positive effects of PA on neglect included patients with at least moderate neglect measurable with diverse visual-spatial tasks. One possibility to explain the absence of PA effects in AB therefore is that PA may only show an effect in patients with moderate to severe neglect.

The alternative (though not exclusive) possibility is that PA only affects certain impairments expressed by patients with right-hemisphere damage. Indeed, negative findings by other research groups suggest that purely visual measures (such as visual search) may not be affected by PA (Morris et al., 2004). This is in line with a recent study showing that neglect patients with a motor-intentional deficit benefited from a 2-week program of PA, while patients classified as having primarily a visual-attentional deficit did not benefit (Goedert, Chen, Boston, Foundas, & Barrett, 2014). A further finding of interest for the interpretation of PA effects on single-word reading is a study by Gossmann, Kastrup, Kerkhoff, López-Herrero, and Hildebrandt (2013), who found that PA only affected body-centered neglect and cancellation, but not line bisection. This finding suggests that the reference frames that are predominantly implicated in these tasks may have distinct dynamics of plasticity and therefore respond differently to the spatio-motor recalibration triggered by PA.

Conclusions

The conclusions that can be reached from a single case are necessarily limited by the nature of functional deficits of the patient. In particular, it is unclear whether AB’s neglect dyslexia was viewer-, stimulus-, or object-centered, though the
dependence of letter errors on word length suggests a strong viewer-centered component. Previous studies have shown that specific neglect dyslexia reading patterns predict the success of a targeted intervention. For example, Daini et al. (2013) found that optokinetic stimulation only affected omission errors, and only in one out of two patients. Such observations may serve as the starting point for larger case studies with the ultimate goal to identify individualized and targeted interventions for specific impairments.

In sum, while not invalidating the use of PA for the therapy of spatial neglect, the present findings support the conclusion that single-word reading may not be significantly enhanced by this procedure in pure neglect dyslexia. Patients with relatively pure forms of the disorder may better be treated using visual-attentional training (e.g., scanning exercises, oculomotor exploration, saccadic training), while PA should be reserved for patients with motor-intentional and egocentric forms of neglect.

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