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The neural correlates of object-centered processing in reading: A lesion study of neglect dyslexia

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ABSTRACT

Neglect dyslexia – a peripheral reading disorder generally associated with left spatial neglect – is characterized by omissions or substitutions of the initial letters of words. Several observations suggest that neglect dyslexia errors are independent of viewer-centered coordinates; the disorder is therefore thought to reflect impairment at the level of object-centered representations. This hypothesis is indirectly supported by lesion studies connecting object-centered neglect errors with damage to posterior cortical regions lying in the ventral visual stream. Here, we performed a lesion-symptom mapping study of 40 patients with spatial neglect asked to read words presented at different positions relative to a viewer-centered coordinate frame. We found that the frequency of object-centered reading errors was constant across horizontal positions, whereas the frequency of entirely neglected words (reflecting a page-centered deficit) linearly increased from right to left. Damage to the intraparietal sulcus and the angular and middle temporal gyri was the best predictor of object-centered errors. We discuss these findings with reference to a role of the posterior parietal lobe in adapting the size of the attentional focus and biasing object representations elaborated in the ventral visual stream.

1. Introduction

Neglect dyslexia (ND) is a reading disorder characterized by omissions or substitutions of the initial letters of words (Ellis, Flude, & Young, 1987; Kinsbourne & Warrington, 1962). Although several patients with damage to the left hemisphere and reading errors affecting the end of words have been reported (Caramazza & Hillis, 1990; Miceli & Capasso, 2001) patients with ND typically have left spatial neglect following right brain damage (Vallar, Burani, & Arduino, 2010). The impairment characterizing ND is considered to affect peripheral stages of reading, which specify processing of perceptual features of the stimulus and its spatial coordinate frame. The study of ND therefore not only gives an opportunity to examine the interdependence between central and peripheral reading processes, but also contributes to the understanding of the spatial representations necessary for reading and object processing.

Marr's model of visual recognition (Marr, 1982) has inspired an influential theoretical account that proposes to classify distinct patterns of ND according to whether the deficit affects a viewer-centered, a stimulus-centered, or a word-centered representation (Hillis & Caramazza, 1995). The viewer-centered representation specifies individual features of letters in terms of shape primitives (bars, edges or discontinuities) whose spatial arrangement and position are coded with respect to the egocentric reference frame of the viewer. If ND errors depend on a viewer-centered coordinate frame, varying the position of the stimulus with respect to the viewer will significantly affect the degree of ND. In the stimulus-centered representation features are letter shapes, and their coordinate frame is defined by the boundaries of the word. Thus, the 'left' side of the word is defined relative to the viewer, but the absolute position of the word does not matter. ND errors that are coded within the stimulus-centered representation will therefore not vary as a function of whether a word is printed on the left or right side of the sheet. In contrast, ND errors that depend on the word-based representation are invariant across different orientations of the stimulus, because the spatial arrangement of features in this representation is coded in canonical coordinates. Throughout this paper we will use the more common term *object-centered* when referring to neglect errors affecting the left side of words independently of their horizontal arrangement on the page, and *page-centered* when referring to omissions of entire words located on the left side of the sheet.

The Hillis–Caramazza model finds support in reports of patients with pure object-centered (Haywood & Coltheart, 2001) or word-centered deficits (Caramazza & Hillis, 1990; Miceli & Capasso, 2001), observations of viewer-independent neglect with rotated

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stimuli whose coordinate frame strongly depends on an intrinsic axis (Behrmann & Moscovitch, 1994; Behrmann & Tipper, 1999; Driver & Halligan, 1991) and the finding that manipulations of the viewer-centered reference frame (e.g., by head rotation) affect awareness of left-sided stimuli without influencing ND errors (Reinhart, Keller, & Kerkhoff, 2010). However, the idea that neglect becomes manifest in purely object-centered coordinates has been challenged on the basis of evidence suggesting that processing of rotated objects may reflect the rotation of a viewer-dependent representation rather than expression of viewer-independent coding (Buxbaum, Coslett, Montgomery, & Farah, 1996). Also, as some experimental manipulations do not disentangle viewer-centered and object-centered reference frames unambiguously the independence of these two levels of representation has been questioned. Thus, Driver and Pouget (2000) argued that seemingly object-centered effects can readily be explained in terms of 'relative egocentric' neglect – provided one assumes that the spatial gradient determining neglect is steeper *within* than *between* objects.

Characterizing the functional anatomy of object-centered and viewer-centered errors in ND may help to clarify the question whether these two types of processing reflect distinct spatial representations. According to some studies, a bias favoring object-centered processing might result from damage to occipito-temporal cortex (Binder, Marshall, Lazar, Benhamin, & Mohr, 1992; Golay, Schnider, & Ptak, 2008; Rorden, Fruhmann Berger, & Karnath, 2006), rather than more dorsal and anterior regions mediating spatial attention. This suggestion was mainly based on the finding that a large ipsilesional bias on line bisection is associated with more posterior brain damage. However, the significance of this conclusion is limited by the fact that line bisection is not a pure measure of perceptual neglect, but reflects a mixture of perceptual, motor and attentional biases.

Here, we compared for 40 patients with left spatial neglect the distribution of omissions of entire words (reflecting page-centered processing) and the distribution of ND errors (reflecting object-centered processing) for words arranged at different positions relative to the viewer. These distributions should be comparable if they depend on the same spatial gradient – possibly reflecting damage to the same spatial representation (for a similar approach, see Chechlacz et al., 2010; Ota, Fujii, Suzuki, Fukatsu, & Yamadori, 2001). According to the relative-egocentric neglect hypothesis, the number of neglected words should gradually increase from right to left, and a parallel increase in the number of ND errors should be observed. We then sought to identify the brain regions that are the best predictors of ND. Previous lesion studies found substantial variability of the neural correlates of viewer-centered and object-centered processing. Thus, according to several studies object-centered processing in neglect depends on the inferior and lateral temporal lobe (Chechlacz et al., 2010; Hillis et al., 2005; Ptak & Valenza, 2005) or the parahippocampal gyrus (Grimsen, Hildebrandt, & Fahle, 2008). Similarly, object-centered word-reading deficits in ND were associated with posterior inferior temporal, lateral occipital and inferior occipito-temporal damage (Lee et al., 2009; Medina et al., 2009). In contrast, viewer-centered neglect has been linked to damage to the angular, the supramarginal, and the postcentral and anterior superior temporal gyri (Chechlacz et al., 2010; Hillis et al., 2005; Medina et al., 2009), as well as the premotor cortex (Grimsen et al., 2008). These findings suggest that object-centered representations are elaborated in the ventral visual stream – which is concerned with processing of visual forms and objects – while viewer-centered representations are associated with the dorsal 'where'-pathway (Ungerleider & Mishkin, 1982). However, there also seems to be substantial overlap between viewer-centered and object-centered representations. For example, in the only previous large-scale study examining the anatomy of ND (Lee et al., 2009), reading errors reflecting impaired object-centered processing were associated not only with inferior occipito-temporal, but also with parietal white matter damage reaching into the intraparietal sulcus. In addition, Chechlacz et al. (2010) found that the temporo-parietal junction was involved in viewer-centered as well as object-centered processing. In the present report, we show that brain areas whose damage predicts ND involve distinct parietal and temporo-occipital foci, suggesting that a bias favoring object-centered processing in reading results from an interaction between dorsal and ventral processing streams.

2. Materials and methods

2.1. Participants

Forty patients with left spatial neglect (20 females) and 14 right-hemisphere (RH) damaged control patients without neglect (5 females) participated in this study. Approval was obtained from the ethical committee of the University Hospitals Geneva, and all participants gave written consent. All neglect tests (including the reading test) were performed within one week while patients were hospitalized for neurorehabilitation following a first-ever ischemic or hemorrhagic stroke. Since the focus of this study was on neglect dyslexia, we did not attempt to equalize the number of neglect and control patients. The latter were merely included in order to check whether the anatomy of our neglect group was comparable to previous studies.

Table 1 shows demographic data and the results of clinical testing of neglect and control patients. Visual fields were assessed with computerized perimetry (white dot presented on black background for 150 ms at 110 different positions in the left/right hemifield) and/or clinical confrontation. Nine patients of the neglect group had left homonymous lateral hemianopia and one patient inferior quadrantanopia. In the control group, three patients had hemianopia and one patient superior quadrantanopia. All neglect patients manifested behavioral signs of left unawareness (e.g., failure to notice objects or persons placed on their left, right deviation of head or gaze) and lateralized failures in at least two of the following neglect tests: 'Bells' cancellation (Gauthier, Dehaut, & Joanette, 1989), cancellation of inverted among upright Ts (Ptak, Schnider, Golay, & Müri, 2007), E&R cancellation (Wilson, Cockburn, & Halligan, 1987), line bisection (Schenkenberg, Bradford, & Ajax, 1980), sentence copying (Wilson et al., 1987), and copying a landscape. While neglect and control patients had similar age and time since injury, the neglect group had significantly larger lesions and scored significantly worse compared to RH-controls on all neglect tests (Table 1).

2.2. Stimuli and procedure

Patients were asked to read 40 words written in capital letters (14 point Arial), scattered pseudo-randomly on an A4-sheet of paper. Words were composed of 10–12 letters and 2–4 syllables, and had 0–2 orthographic neighbors and a mean frequency of 9.7 per thousand according to the *Lexique* database of written French (http://www.lexique.org; New, Pallier, Brysbaert, & Ferrand, 2004). For half of the words the last 4–6 letters could form a word (e.g., 'sphere' in 'ATMOSPHERE'), while for the other half reading only the last letters would give no sense (such as 'BIJOUTERIE').

Words were arranged in five columns, each containing eight stimuli whose within-column position was determined by first aligning all words regularly and then adding horizontal and vertical jitter so as to give the impression of a random arrangement. Patients were instructed to read aloud all words on the sheet, and the experimenter noted all responses on a separate sheet.

Neglect patients with ND were differentiated from non-ND patients on the basis of their errors in the reading task. Following Ellis et al. (1987) ND errors were defined as omissions or substitutions of letters to the left of an identifiable neglect point in each word. Patients making at least two such errors were considered to have ND ($n = 19$), and were compared to patients who made no ND errors ($n = 18$). The remaining 3 patients made only one ND error and were therefore not included in the anatomical analysis. We chose a liberal criterion for the distinction of ND from non-ND patients because the words presented in our reading task made ND errors unlikely due to their low number of orthographic neighbors (a factor that strongly affects the frequency of ND errors, see Riddoch, Humphreys, Cleton, & Fery, 1990). Note also, that a categorical distinction between ND and non-ND patients is necessary for the lesion-subtraction analysis, but not for lesion mapping using the Brunner–Munzel test (see below), as the latter establishes an anatomical correlation with a continuous functional measure.

2.3. Lesion mapping

32 neglect patients and 12 patients of the RH-control group underwent structural magnetic resonance imaging (MRI) including axial FLAIR, T1- and T2-weighted acquisitions with a between-slice resolution of 4 mm, on a 1.5 T MRI scanner (Siemens Vision, Munich, Germany). For the remaining patients lesion analysis was based on a CT-scan. Brain scans were acquired on average 63.4 days following