
Word-centred Neglect Dyslexia: Evidence from a New Case

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Abstract

Neglect dyslexia resulting from damage to word-centred representations is extremely rare. We report on a new case. A left-handed subject, SVE, presented with aphasia and neglect dyslexia/dysgraphia following a right hemisphere stroke. In tachistoscopic reading tasks, some of his errors resulted from retina-centred neglect, as he responded more accurately to words flashed in the left visual field than to words flashed in the right visual field. However, the critical aspects of his reading performance indicated word-centred neglect. SVE incorrectly produced the initial elements of four-letter words, regardless of stimulus location (to the left and to the right of fixation, or at fixation), and orientation (horizontal and vertical presentation). A similar distribution of errors was demonstrated in writing (very inaccurate performance on initial letters). This pattern of performance suggests damage to an abstract letter string representation defined by spatial coordinates, rather than to an ordering mechanism. It is most naturally accommodated by models of word recognition which assume a word-centred level of representation, and cannot be explained by models which do not include such a representational level. Consideration of our subject in the light of other similar reports prompts hypotheses on the neural mechanisms involved in computing word-centred representations.

Introduction

In recent years, studies of spatially specific reading disorders have been used to draw inferences on the mechanisms involved in recognition and lexical access of written words. Analyses of dyslexic subjects whose reading errors are restricted to the contralesional half of the word have shown that an apparently simple task like recognizing a written word requires a complex set of cognitive/neural mechanisms, each of which can be selectively impaired as a consequence of brain damage. The investigations reported so far are consistent with the hypothesis that word recognition requires the computation of at least three distinct levels of representation (Caramazza and Hillis, 1990; Haywood and Coltheart, 2000). At the retina-centred level, a feature map representation is computed, which represents the lines, curves and blobs comprising the letter string, in a space corresponding to the visual field of the subject. At this stage, the elements in the written input string are coded in terms of their absolute positions in the visual field. At the stimulus-centred level, a letter shape map is obtained, that specifies the form of each letter, and its spatial relations to the other letters in the stimulus. The spatial coordinates at this level correspond to those of the stimulus, so that, even though the representation is still veridical (e.g. the stimulus-centred representation of

a word arranged vertically is a vertical sequence of letter shapes), the absolute position in the visual field is not coded. At the word-centred level, a canonical description of the abstract letter representations in the stimulus and of their relative positions is computed. The elements comprising each stimulus are arranged horizontally, from left to right (at least in languages which are read and written from left to right, like Italian, English, French, etc.), centred with reference to the resulting string. This representation is no longer veridical, and is invariant with respect to the physical properties of the stimulus, like case, font, orientation, and location in the visual field. This pre-lexical orthographic representation serves as input for reading both familiar and novel words. In the former case, it activates stored lexical representations, in the latter, it is processed by grapheme–phoneme sublexical conversion procedures¹.

Damage to any of these representational levels results in contralesional errors when the subject is asked to read words or pseudowords presented horizontally at the centre of the visual field. In the event of a lesion in the right hemisphere, initial letters will be affected by retina-centred damage because they fall in the left hemifield, and by stimulus-centred and word-centred damage because they occupy the

leftmost positions in the sequence of letter shapes or of abstract letter identities represented at these levels, respectively. However, manipulating stimulus location and orientation will yield distinct patterns of impairment, depending on which level is affected. Because the retina-centred representation codes absolute feature location in the visual field, damage to this level yields errors on letters presented in the contralesional hemifield, and normal performance on letters presented in the ipsilesional hemifield (Riddoch *et al.*, 1990; Behrmann *et al.*, 1990; Rapp *et al.*, 1991; Hillis and Caramazza, 1995a, b; Hillis *et al.*, 1998). By contrast, subjects with damage to the stimulus-centred or word-centred level of representation read aloud incorrectly the contralesional half of a stimulus, irrespective of whether it appears in the ipsilesional or contralesional hemifield. This is because the two representations code the relative position of the elements of the written string instead of their absolute position, as is the case at the retina-centred level. Damage to either of these levels can be distinguished by manipulating the input string. The stimulus-centred representation no longer specifies absolute position, but retains other properties of the stimulus, like orientation for example. It codes a stimulus presented vertically in the left visual field as a vertical sequence of letter shapes, centred in the representational space with reference to the viewer. Hence, an impairment at this level allows correct performance in reading stimuli presented vertically (Ellis *et al.*, 1987a; Behrmann *et al.*, 1990; Riddoch *et al.*, 1990; Young *et al.*, 1991; Siéoff, 1991; Hillis and Caramazza, 1991, 1995a; Subbiah and Caramazza, 2000). By contrast, the word-centred representation consists of a string of abstract letter identities arranged horizontally, centred with respect to the centre of the stimulus, and oriented from left to right, regardless of the absolute position, size and orientation of the stimulus. In the event of damage to this level, attempts at reading a stimulus presented vertically result in spatially specific errors restricted to the contralesional half of the string (to initial letters in the case of right brain damage and to final letters in the case of left brain damage), identical to those observed in reading stimuli presented horizontally (Caramazza and Hillis, 1990). By the same token, when a stimulus is presented in a mirror-reversed fashion, letters shown in the ipsilesional hemifield are affected (in the same experimental condition, stimulus-centred damage yields errors on letters shown in the contralesional hemifield).

Spatially specific reading deficits have been given alternative explanations in the context of a different proposal concerning the architecture of the cognitive processes underlying spatial attention and early reading processes. On this account, word recognition does not require distinct levels of representation, and takes place by virtue of massively interacting computations (Mozer, 1987, 1988; Mozer and Behrmann, 1990). Unfortunately, models of this type were allegedly designed to account only for neglect dyslexia (and other neglect phenomena) occurring in a viewer-based coordinate system, and were not explicitly concerned with neglect resulting from damage to object-centred representa-

tions. Thus, they cannot accommodate subjects like NG, who incorrectly read the contralesional elements of an abstract graphemic string, even when shown in the ipsilesional hemifield. This limitation has not raised particular interest, as word-centred neglect dyslexia is exceedingly rare, and the only report on record after case NG (Caramazza and Hillis, 1990) is DES (Greenwald and Berndt, 1999), in whom a similar reading and spelling disorder was attributed not to a spatial, but to a positional disorder. Thus, new cases of word-centred neglect dyslexia are of particular interest in the current debate on the functional architecture of the mechanisms involved in word recognition.

Word-centred neglect dyslexia also raises intriguing questions related to brain/behaviour relationships. First of all, there are very few reports of this disorder following unilateral brain damage. In most cases, word-centred neglect dyslexia was inferred a posteriori, by analogy with the pattern of performance reported for NG (Baxter and Warrington, 1983; Barbut and Gazzaniga, 1987; Hillis and Caramazza, 1995a). The total count of subjects with word-centred damage also remains low when we consider the very few cases with 'dual neglect' (i.e. left neglect dyslexia, and right-side neglect for other visual stimuli), that usually follow bilateral brain damage [Costello and Warrington, 1987; Humphreys and Riddoch, 1995; but see Riddoch *et al.* (1995)]. This contrasts with the relatively larger number of subjects with damage to retina-centred or stimulus-centred representations [see reports quoted previously and, for recent reviews, Hillis and Caramazza (1995a) and Haywood and Coltheart (2000)]. Second, word-centred neglect dyslexia occurs in very different contexts from those in which retina- and stimulus-centred damage are observed. To mention the most obvious difference, retina- and stimulus-centred neglect were essentially only reported in dextrals with right hemisphere damage. By contrast, word-centred neglect was observed in left handers after damage to the left hemisphere (NG, Caramazza and Hillis, 1990) and to the right hemisphere (ORT, Baxter and Warrington, 1983; JR, Barbut and Gazzaniga, 1987; ML, Hillis and Caramazza, 1995b), and in right handers after lesions to the left hemisphere (RYT, Warrington, 1991; HB, Hillis and Caramazza, 1995b; DES, Greenwald and Berndt, 1999), but never in dextrals after right hemispheric damage. There is no apparent reason for this asymmetry. An obvious corollary of the reported distribution of lesions is that the various forms of neglect dyslexia are associated to very different neuropsychological profiles. All subjects with retina- and stimulus-centred dyslexia show obvious neglect phenomena in purely visual-spatial tasks [in a recent review, Haywood and Coltheart (2000) propose a different interpretation of some published cases, which suggests that stimulus-centred neglect dyslexia and visual neglect might dissociate]. By contrast, visual neglect in subjects with word-centred neglect dyslexia ranges from marked (NG, Caramazza and Hillis, 1990) to minimal (HB, Hillis and Caramazza, 1995b). Conversely, retina- and stimulus-centred dyslexia were never reported in association

with aphasia, whereas this association is almost systematic for word-centred dyslexia (with the exception of NG; Caramazza and Hillis, 1990).

The extreme heterogeneity of the reported subjects with respect to handedness, lesion side and site, presence/severity of aphasia and of visual neglect does not in the least invalidate the conclusions concerning the role of word-centred representations in reading, as this problem can be discussed (at least for the time being) largely independently of neuroanatomical considerations, but it raises interesting questions on the organization of word recognition mechanisms in the brain. Additional cases of word-centred neglect dyslexia are needed in order to answer these questions. We report here on a new subject, who presents with this rare disorder.

Case history

SVE is a 70-year-old man, with high-school education. A corrected left hander, he was instructed at school to use his right hand, which he has used since as his preferred hand. He worked as a jewel maker, and then as an engraver at the Bank of Italy. He suffered ischaemic damage to the right hemisphere in October 1994, and was referred to us 30 months later. The neurological examination revealed a dense left hemiplegia. No elementary tactile, visual or auditory deficits could be detected upon clinical examination, but unsystematic left-sided extinction phenomena were observed in all modalities (tactile, visual, acoustic) on double simultaneous stimulation. The present study was conducted between April 1997 and October 1998. A magnetic resonance imaging (MRI) scan (July 1998) demonstrated an extensive lesion in the anterior and central branches of the right middle cerebral artery (Fig. 1). The damage involved most of the frontal lobe, the insula, the basal ganglia, the extreme and external capsule, with at least partial damage to the thalamus and the head of the caudate nucleus. The lesion extended posteriorly into the parietal lobe, where it mostly involved the white matter, and, inferiorly into the white matter of the anterior portions of the temporal lobe, with questionable involvement of the pole. Bilateral ventricular dilation, much more marked on the right, was also present.

Neuropsychological and language examination

Constructional abilities were spared. No ideomotor apraxia was detected, but buccofacial apraxia was evident. SVE produced 25/36 correct responses on Raven's Colored Progressive Matrices. On phonological short-term memory tasks, he made errors even when repeating the shortest (two items) series of bisyllabic words and of bisyllabic pseudowords. On memory probe tasks, he was just below normal with words, and moderately impaired with pseudowords.

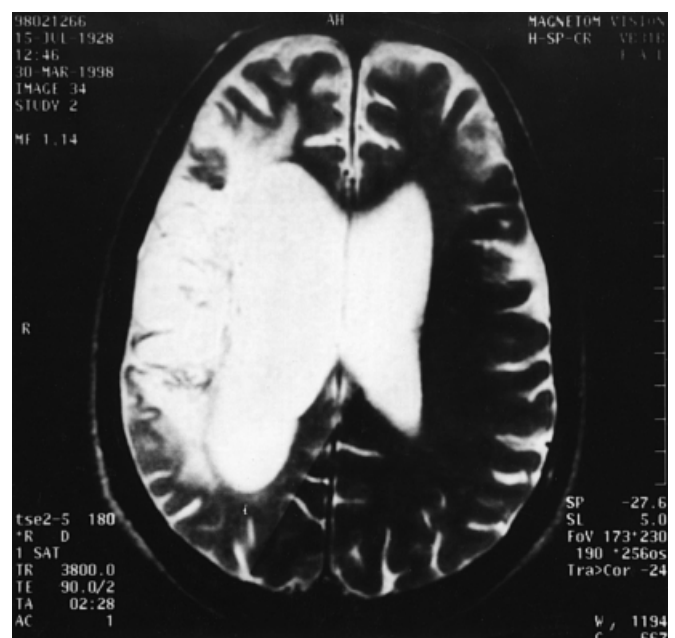
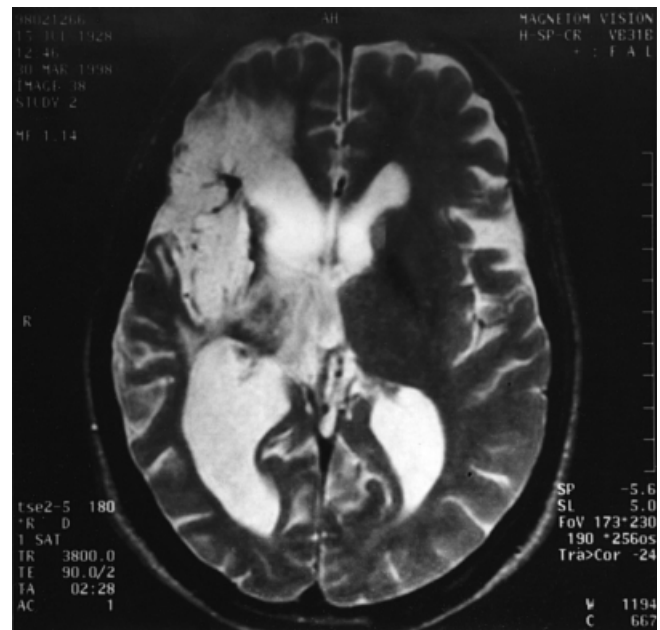


Fig. 1. Representative sections of the magnetic resonance imaging scan showing extensive damage to the right hemisphere.

Visuo-spatial tasks

SVE was asked to bisect six lines 50, 150 and 200 mm in length, and 12 lines 100 mm in length. Each line was presented separately, centred on an A4 sized sheet. Our subject first had to mark the endpoints, then the midpoint of each line. He did not demonstrate systematic neglect phenomena on this task. In some cases, he marked the right endpoint before the left. He shifted the subjective midpoint of 50 mm lines to the left by 1 mm on average (2% of line length), and that of all the other lines to the right (100 mm: 2.2 mm, or 2.2% of line length; 150 mm: 2.7 mm, or 1.8%

of line length; 200 mm: 7.5 mm, or 3.7% of line length). Thus, even though the predicted rightward shift of the subjective midpoint occurred (at least, for lines of 100 mm or longer), it was always minor.

In line cancellation tasks, SVE omitted 2/40 lines in the lower left corner of the page when the stimuli were presented without gaps, and 2/40 lines when the stimuli were grouped on the left and on the right of the page, with a 5-cm unfilled gap at the centre. In the latter task, he omitted the two leftmost items in the group positioned on the left side of the page. He also found 20/20 symbols and 20/20 letters in search tasks administered on A3 sized paper. On some of these tasks, he scanned the page from right to left.

Our subject copied the Ogden scene flawlessly, and omitted only a small detail in the left upper corner of Rey–Osterrieth's complex figure, which he otherwise produced accurately. In both tasks, he proceeded from left to right.

In two further tasks, SVE was asked to report whether two letters presented tachistoscopically were identical or different. 'Same' pairs consisted of two Xs or two Os, and 'different' pairs of one X and one O. The letters were presented simultaneously. In each task, there were 20 'same' and 20 'different' pairs. SVE was invited to decide whether the two letters he had been presented with were the same or different. Each pair was presented for 100 ms. The location of the letters differed in the two tasks. In one, the letters were arranged in five horizontal locations, all placed on a line going through the centre of the screen: central fixation, 1° of visual angle to the left or to the right of fixation, and 2° of visual angle to the left or to the right of fixation. In the other, they were arranged in five vertical locations along a line going through the centre of the screen: central fixation, 1° of visual angle above or below fixation, and 2° above or below fixation. All possible combinations of locations on each line were used ($n = 10$), and an equal number of 'same' and 'different' pairs was shown at each location on each line. Overall, two letters in identical pairs and two in different pairs were presented at each location. There were 40 letter pairs in each task. In both tasks, SVE performed without errors.

In summary, visuo-spatial tasks demonstrated very minor, unsystematic left-sided neglect.

Language tasks

The results obtained by SVE on a test battery for aphasia (Miceli *et al.*, 1994) are summarized in Table 1.

Auditory input processing was mildly impaired, as shown by the results in discrimination and auditory–picture matching of minimal pairs of phonemes, in repetition of pseudowords and in auditory lexical decision. SVE spoke slowly and with great effort, in a very low voice, but without articulatory problems. Speech was severely 'agrammatic', and sometimes reduced to one-word utterances. Omissions of function words and main verbs were very frequent. Anomia was severe for verbs, mild for nouns; occasional phonemic paraphasias

were also observed. Auditory comprehension was clinically unimpaired at the single-word level (for both nouns and verbs), and moderately impaired at the sentence level. Repetition was mildly impaired for pseudowords of one to three syllable length (29/36 correct responses, 80.6%), and essentially normal for polysyllabic words (43/45 correct responses, 95.6%). Errors on pseudowords occurred across all positions; incorrect responses to words resulted in inflectional errors (ciliegia, cherry → ciliege, cherries).

Tasks that required the ability to process written words yielded the most intriguing errors (examples are reported in Table 2). In a visual word–picture matching task, SVE was asked to match 40 written nouns and 20 written verbs to one of two pictures, corresponding to the target and to a semantic foil in half of the stimuli or to a visual foil in the remaining half. He responded correctly to 37/40 nouns (92.5%) and 13/20 verbs (65%). With two exceptions (both semantic errors to verbs), incorrect responses resulted from the selection of the visual foil to a noun (3/20, 15%) or to a verb (5/10, 50%). In all cases, the stimulus and foil differed by one letter in the word-initial position. In reading aloud, SVE produced significantly more correct responses to words (70/92, or 76.1%) than to pseudowords (10/45, or 22.2%); $\chi^2 = 33.905$; d.f. = 1; $P < 0.001$. Irrespective of stimulus type, most errors could be construed as the result of a difficulty in producing stimulus-initial letters (words: 21/22; pseudowords: 30/35).

Because these results raised the suspicion of a spatially specific dyslexia, SVE was submitted to further tasks aimed at better understanding the mechanisms responsible for his reading deficit.

Experimental study

Reading words with unlimited presentation

In order to evaluate the factors influencing performance in word reading, SVE was asked to read aloud 272 words and 122 pseudowords. The words were included in various sublists (each word could be included in more than one sublist).

Scoring procedure. The same scoring criteria were used for all the reading tasks administered in the course of this project. In addition to the gross quantitative aspects of performance, response accuracy to individual letters of each stimulus was evaluated for each task. Words of the same length and presented in the same position in the visual field were grouped, and errors in producing letters at various positions within the stimulus were examined, in order to establish the presence of spatially determined reading errors. Incorrect letters were scored as follows. Letter substitutions or omissions were counted as one error in the position in which the error occurred. For example, *cento*, hundred → 'mento', chin and *fruga*, he searches → 'ruga', furrow were scored as a substitution and as an omission error in position 1 of five-letter words, respectively. Similarly, *grossa*, big,

Table 1. Correct responses produced by SVE on the subtests of the BADA (Miceli *et al.*, 1994). Percentages are in parentheses

Phoneme discrimination		51/60 (15.0)	'Same' pairs: 26/30 (86.7)	'Different' pairs: 25/30 (83.3)
Auditory-visual matching		46/60 (23.3)	'Same' pairs: 26/30 (86.7)	'Different' pairs: 20/30 (66.7)
Pseudoword tasks	a. repetition	29/36 (80.6)		
	b. dictation	interrupted		
	c. delayed copy	1/6 (16.7)		
	d. reading aloud	10/45 (22.2)		
Lexical decision	a. auditory	72/80 (90.0)	Words: 35/40 (87.5)	Pseudowords: 37/40 (92.5)
	b. visual	53/80 (66.2)	Words: 35/40 (87.5)	Pseudowords: 18/40 (45.0)
Word transcoding tasks	a. repetition	43/45 (95.6)		
	b. dictation	interrupted		
	c. delayed copy	0/10 (0.0)		
	d. reading aloud	70/92 (23.9)		
Auditory word-picture match	a. nouns	40/40 (100)	Semantic foils: 20/20 (100)	Phonemic foils: 20/20 (100)
	b. verbs	20/20 (100)	Semantic foils: 10/10 (100)	Phonemic foils: 10/10 (100)
Visual word-picture match	a. nouns	37/40 (92.5)	Semantic foils: 20/20 (100)	Visual foils: 17/20 (85)
	b. verbs	13/20 (65.0)	Semantic foils: 8/10 (80)	Visual foils: 5/10 (50)
Spoken naming	a. nouns	26/30 (86.7)		
	b. verbs	10/28 (25.7)		
Written naming	a. nouns	0/28 (0.0)		
	b. verbs	0/28 (0.0)		
Spoken naming to definition	nouns	11/16 (68.7)		
Grammaticality judgements	a. auditory	40/48 (83.3)	Grammatical: 18/24 (75)	Ungrammatical: 22/24 (91.7)
	b. visual	14/24 (58.3)	Grammatical: 7/12 (58.3)	Ungrammatical: 7/12 (58.3)
Sentence transcoding tasks	a. repetition	8/20 (40.0)		
	b. reading aloud	2/6 (33.3)		
Sentence-picture matching	a. auditory	46/60 (76.7)	Reversals: 14/20 (70)	Morpho foils: 15/20 (75) Semantic foils: 17/20 (85)
	b. visual	32/45 (71.1)	Reversals: 8/15 (53.3)	Morpho foils: 12/15 (80) Semantic foils: 12/15 (80)

f.sg. → 'scossa', quake was scored as two substitution errors in positions 1 and 2 of a six-letter word, and so on. For each inserted letter, 0.5 point was assigned to the positions preceding and following the insertion (*banco*, bench → 'bianco', white was scored as 0.5 errors in positions 1 and 2). For letter exchange errors, one point was assigned to each letter produced in an incorrect position (*limite*, limit → 'milite', soldier was scored as an error in position 1 and an error in position 3; *parti*, parts → 'prati', meadows was scored as an error in position 2 and an error in position 3, and so on).

Also, complex errors involving more than one letter were scored. Errors on word-initial letters, resulting in a response whose length differed from the target by more than one letter, were scored as one point in the first position, irrespective of the number of letters by which the stimulus and response differed (*viva*, alive, f.sg. → 'saliva', he was climbing was scored as one error in the first position). Such errors never occurred in word-final positions. For responses showing no obvious relationship to the stimulus (e.g. *lumi*, lamps → 'mese', month), the entire string was scored as incorrect, and one point was assigned to each letter position. Failures to respond were scored similarly. The error types listed in this paragraph were very rare. All the incorrect responses produced by SVE were retained for analysis, unless otherwise indicated.

Results

Words. SVE correctly produced 186/272 words (68.4%). Performance accuracy was not affected by abstractness/concreteness, length, and frequency of usage. Our subject

Table 2. Examples of incorrect responses produced during the screening procedure in tasks that required the ability to process written words

Word to picture matching (subject is shown a written word and has to match it to one of two pictures corresponding to the target and a semantic foil, or to the target and a visual foil)

Stimulus	Visual foil selected by SVE
<i>freccia</i> , arrow <i>legare</i> , to bind <i>contare</i> , to count	treccia, ponytail segare, to saw cantare, to sing
Reading pseudowords aloud	
Stimulus	Response
<i>go</i> <i>coba</i> <i>digaro</i> <i>ravilo</i> <i>volidia</i>	'congo' 'roba', stuff 'sigaro', cigar 'giovilò', pseudoword 'vidia', pseudoword
Reading words aloud	
<i>banche</i> , banks <i>bando</i> , notice <i>regalato</i> , given <i>inventata</i> , invented <i>tomba</i> , grave <i>frecce</i> , arrows	'bianche' white, f.pl. 'quando', when 'gelato', ice cream 'spaventa', scared 'bomba' bomb 'precce', pseudoword

was similarly accurate in reading frequency- and length-matched lists of abstract and concrete nouns (concrete: 24/30 correct, 80%; abstract: 20/30 correct, 66.7%;

$\chi^2 = 0.767$; d.f. = 1; $P = \text{n.s.}$). He was comparably accurate in reading frequency-matched subsets of short words (four to six letters) and long words (seven to nine letters): he produced 42/64 short words, or 65.6% and 44/64 long words, or 68.7% correctly ($\chi^2 = 0.300$; d.f. = 1; $P = \text{n.s.}$). His performance on length-matched subsets of medium-frequency (20–50/million) and low-frequency (10/million or lower) words was also similar (medium frequency: 45/64 correct, 70.3%; low frequency: 41/64 correct, 64.1%; $\chi^2 = 0.319$; d.f. = 1; $P = \text{n.s.}$). At face value, accuracy was affected by grammatical class, as SVE correctly read aloud 29/32 nouns (90.6%) and 25/32 adjectives (78.1%), but only 17/32 verbs (53.1%) ($\chi^2 = 12.110$, d.f. = 1; $P < 0.01$). Because he was also more impaired on verbs than on nouns in spontaneous speech and in picture naming, it would not be unreasonable to ascribe this pattern to a grammatical class effect. However, poor performance on verbs in reading might easily result from neglect dyslexia. Because in Italian most verb forms have multi-letter inflections, difficulty in processing word-initial letters would result in responses relying heavily on information on inflectional endings. Because each inflection is shared by all the verbs belonging to the same conjugation, each verb form provides many opportunities for neglect-based errors. And in fact, 12/15 (80%) incorrect responses to verbs resulted in forms of other verbs containing the same inflection as the stimulus [e.g. *perdere*, to lose → ‘vedere’, to see; *morendo*, dying → ‘correndo’, running; *unirono*, they united → ‘sparirono’, they disappeared, etc. (inflectional endings are underlined)]. Thus, it is likely that a grammatical class effect plays only a minor role in SVE’s reading performance.

All errors to words ($n = 86$) resulted in an incorrect word. Most (76/86, 88.4%) could be scored as neglect based. In these responses, the errors involved only one or more initial letter (e.g. *costo*, cost → ‘posto’, place; *stima*, esteem → ‘clima’, climate; *denuncio*, I denounce → ‘rinuncio’, I renounce; *vivente*, living → ‘spiovente’, slanted). In three cases, both initial and non-initial letters were produced incorrectly (e.g. *siccome*, since → ‘dorme’, he sleeps; *usavano*, they were using → ‘posavamo’, we were putting down; *misteri*, mysteries → ‘pensieri’, thoughts). In four other cases, errors occurred in non-initial positions (*motto* → ‘moto’, movement; *palla*, ball → ‘pala’, shovel; *valga*, that it is worth → ‘vaga’, vague; *cercavano*, they were searching → ‘cercavamo’, we were searching). The four remaining responses are difficult to interpret. In all cases, final letters were produced correctly, but initial letters were involved in complex errors (*circonda*, surrounds → ‘comoda’, comfortable; *volgare*, vulgar → ‘spigolare’, to browse; *impariamo*, we learn → ‘paragoniamo’, we compare). Incorrect responses clearly tended to preserve stimulus length (correlation coefficient: 0.588; $P < 0.001$), as 77/86 (89.5%) differed from the stimulus by no more than two letters. Of these, 33 had the same number of letters (38.4% of total incorrect responses) as the stimulus, 23 (26.7%) differed by one letter, and 21 (24.4%) differed by two. Of the 44 incorrect responses that

Table 3. Reading aloud words of different lengths (untimed presentation). Incidence of incorrect responses in reproducing each letter in words of four letters ($n = 26$), five letters ($n = 115$), six letters ($n = 40$), seven letters ($n = 37$), eight letters ($n = 31$), and nine letters ($n = 21$). Words are aligned with respect to their centre. Results are expressed as the percentage of incorrect responses

Length	X									
4				30.8	3.8	3.8	0			
5			24.3	7.8	7	0.9	0			
6		15	15	2.5	5	0	0			
7		43.2	35.1	21.6	8.1	1.3	4	0		
8	29	25.8	21	9.7	4.8	3.2	0	0		
9	23.8	14.3	6.5	6.5	0	0	0	3.2	0	

differed by one to two letters from the stimulus, 16 were shorter and 28 were longer than the target.

The distribution of errors across within-word positions is presented in Table 3 for stimuli ranging in length from four to nine letters (there were only two words of 10 letters in length in the corpus of stimuli administered to SVE; they were not considered in this analysis). Errors clearly clustered at word beginnings, irrespective of stimulus length, strongly suggesting that our subject suffered from some form of neglect dyslexia. Note that at least one of the two errors in position 6 of seven-letter words (*usavano* → ‘posavamo’) and the only error in position 8 of nine-letter words (*cercavano* → ‘cercavamo’) might have resulted from a difficulty with inflections (SVE also made inflectional errors in spontaneous speech and in repetition tasks). The higher error occurrence on word-initial positions of four-letter words (which are barely into the left visual field) than of nine-letter words (which are well within the left visual field) may seem paradoxical. However, it can be accounted for by considering that stimuli in this list were not controlled for number of orthographic neighbours, and that in general word-initial damage might leave the subject with sufficient information as to constrain the correct response in the case of longer stimuli, but not of shorter stimuli (loss of the three initial letters in *scrivania*, desk, is still compatible only with the correct response, but loss of just the initial letter of *pane*, bread, might result in many incorrect word responses like ‘cane’, ‘lane’, ‘nane’, ‘rane’, ‘sane’, ‘tane’, ‘vane’).

Pseudowords. Performance on pseudowords was extremely poor. SVE managed to produce correctly only 6/122 stimuli (5.9%). The difference in accuracy level for words and pseudowords is highly significant ($\chi^2 = 32.071$; d.f. = 1; $P < 0.001$). The worse performance on this task than on a similar task administered in the context of the screening battery is probably due to the fact that the screening procedure only contained short stimuli (one to three syllables; two to six letters), whereas the list discussed here included only polysyllabic pseudowords (two to four syllables; four to eight letters).

SVE correctly produced 4/16 (25%) stimuli of four to five letters, and 2/106 (1.9%) stimuli of six to eight letters. The comparison is statistically significant ($\chi^2 = 11.324$; d.f. = 1;

$P < 0.001$), but of uncertain value, due to the obvious floor effect. He produced 114 complete incorrect responses (93.4%); he also produced one fragment and one circumlocutory response (0.8% in each case), which were not considered further. Errors to pseudowords resulted in an incorrect word (72, or 59% of total responses) or, with significantly lower frequency, in an incorrect pseudoword (42, or 34.4%) (binomial test: $\chi^2 = 7.903$; $P < 0.01$). As many as 76/114 incorrect responses (66.7%) could be construed as neglect errors, in which the response differed from the target only by one or more initial letter. Of these, 57/76 (75%) resulted in a word (e.g. *vila* → 'fila', line; *rudela* → 'tutela', custody; *catutile* → 'inutile', useless) and 19/76 (25%) in a pseudoword (e.g. *ansola* → 'conisola'; *piaduli* → 'chevuli'; *ilfabera* → 'afabera'). The remaining incorrect responses (38/114, or 33.3%) resulted in complex errors, sometimes showing no obvious relationship to the stimulus. They yielded 15/38 (33.3%) words (e.g. *fineva* → 'cinema'; *pifone* → 'termale', thermal), and 23/38 (66.7%) pseudowords (*neartole* → 'martore'; *etirlope* → 'conicolle'; *greomeno* → 'fenicolio').

The occurrence of 76/114 neglect errors indicates that SVE correctly processed the final letters of the stimulus; that 19/76 neglect errors (25%) resulted in pseudowords suggests at least partial sparing of grapheme-phoneme conversion procedures.

Summary of performance on across the desk reading tasks. In our subject, the response accuracy to words was unaffected by frequency, length, abstractness/concreteness, and grammatical class. SVE was significantly more accurate in reading words as compared with pseudowords—a pattern frequently reported in subjects with neglect dyslexia, and attributed to the fact that a 'completion' strategy relying on information on the spared letters of a stimulus is more likely to yield the correct response when the stimulus is a word than when it is a pseudoword (Caramazza and Hillis, 1990). Most incorrect responses to both words (76/86, or 88.4%) and pseudowords (76/114, or 66.7%) could be construed as the result of left-sided neglect. These errors occurred more often in response to words than to pseudowords ($\chi^2 = 12.322$; d.f. = 1; $P < 0.001$), and resulted almost always in an incorrect word (76/76 neglect errors to words, or 100%; 57/76 errors to pseudowords, or 75%). The pattern of performance documented in this task clearly indicates left-sided neglect dyslexia. The rest of this study is devoted to an attempt at identifying the functional lesion responsible for such a disorder, by means of computerized tasks.

Reading words under tachistoscopic presentation

Methods. This and the following task were presented on a PowerPC Macintosh computer, with a high-definition monitor. In both tasks, the point of fixation corresponded to the centre of the monitor. Each item was started manually by an examiner, who sat next to SVE and pressed the Return

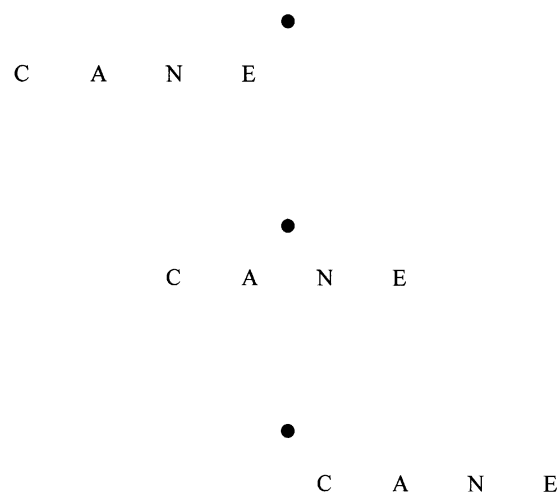


Fig. 2. Absolute position of each letter in four-letter words presented at the three selected locations (centre of locations: 2° of visual angle to the left of the fixation point, at the point of fixation, and 2° of visual angle to the right of fixation). ● = point of fixation (corresponding to the centre of the computer screen).

key. Another examiner sat in front of the subject, in order to ensure that fixation was maintained. All tasks were preceded by a practice block. Items during which SVE shifted his gaze were presented again, in the next session. The results were scored as in the previous task.

Reading aloud four-letter words presented horizontally in various absolute positions in the visual field. Stimuli were presented tachistoscopically at three different locations in the visual field (entirely to the left or to the right of the fixation point or centred at the point of fixation). Damage to the various levels of representation predicts different patterns of performance on this task. Because the retina-centred representation is a veridical map of the discontinuities in the visual field that define a visual trace of the word and because it codes the absolute position of each feature comprising the stimulus, damage to this level predicts poor performance on the materials presented in the contralesional visual field. SVE should inaccurately produce four-letter words shown in the left visual field, as well as the leftmost two letters of the same words presented at the point of fixation, but he should perform accurately on four-letter words presented entirely to the right of fixation and on the rightmost two letters of the same words presented centrally. Furthermore, the performance on letters that appear at the same absolute location in the visual field should be comparable. By contrast, stimulus- and word-centred damage predict errors on initial letters, irrespective of their absolute position in the visual field, as these representational levels code relative, not absolute, positions in the visual field.

A list of 120, four-letter words was used for this experiment. The stimuli were selected so that several orthographic neighbours could result from a loss of information on initial letters. The words were presented in canonical form at three positions, located on the horizontal line going through the point of fixation (Fig. 2). The locations were selected so

that the stimulus appeared an equal number of times entirely to the left of the fixation point, entirely to the right of the fixation point, or centred with respect to the fixation point (in this case, two letters appeared to the left, and two to the right of the fixation point). Left and right locations were centred at 2° of visual angle with respect to the point of fixation, whereas the central location was centred at the point of fixation. At each location, each word was centred so that two letters appeared to the left, and two to the right of the location centre. Thus, letters 3 and 4 of words presented to the left of fixation overlapped with letters 1 and 2 of words presented centrally, and letters 3 and 4 of words presented at the centre overlapped with letters 1 and 2 of words presented to the right of fixation. The fixation point was shown at the centre of the screen prior to the presentation of each stimulus.

In this and the following task, the exposure time was set to 250 ms. This stimulus duration resulted in erroneous performance, without proving too distressing for SVE. Both tasks were administered in several short sessions (usually, 60 stimuli per session; no more than two sessions on the same day, spaced by at least 2 h), over a period of almost a year. Each word was presented twice in each of the three selected locations. Overall, SVE read aloud 720 words (240 in each location).

Our subject produced 425/720 correct responses (59%). He correctly read aloud 126/240 words presented to the left of fixation (52.5%), 144/240 words presented at fixation (60%), and 155/240 words presented to the right of fixation (64.6%). The response accuracy was significantly influenced by absolute stimulus position ($\chi^2 = 7.39$; d.f. = 2; $P < 0.05$). The performance on words presented entirely in the left visual field was significantly less accurate than the performance on words presented entirely in the right visual field ($\chi^2 = 6.73$; d.f. = 1; $P < 0.01$), but it did not differ significantly from the performance on words presented at the fixation point ($\chi^2 = 2.447$; d.f. = 1; $P = \text{n.s.}$). Accuracy levels on words presented at fixation and to the right of fixation were also indistinguishable ($\chi^2 = 0.887$; d.f. = 1; $P = \text{n.s.}$).

A lower accuracy on stimuli presented in the left visual field than on stimuli presented in the right visual field suggests retina-centred damage. However, the high number of errors on stimuli presented entirely in the right visual field suggests that other levels of representation are impaired as well.

This conclusion is very clearly supported by the comparison of error rates to letters presented at the same absolute location in the visual field (Table 4). A purely retina-centred deficit should result in similar error rates on letters that overlap in the visual field, even though they occur at different relative positions in a word. SVE's performance stands in stark contrast with this expectation. He made significantly fewer errors on letter 3 of words presented to the left of fixation than on letter 1 of words presented at the centre ($\chi^2 = 48.1$; d.f. = 1; $P < 0.001$) and on letters 3 and 4 of words

Table 4. Error rate to each letter in reading four-letter words ($n = 120$) presented horizontally in various positions in the visual field. The position of each letter with respect to the point of fixation is shown

		Fixation point							
		●							
1	2	3	4	3	4	1	2	3	4
40.8	20.0	10.8	4.6	2.7	1.3	31.7	7.9	4.4	2.3
		1	2						
		38.5	7.9						

presented at the centre than on letters 1 and 2 of words presented to the right of the fixation point ($\chi^2 = 68.7$; d.f. = 1; $P < 0.001$; $\chi^2 = 10.7$; d.f. = 1; $P < 0.005$, respectively). Furthermore, our subject produced significantly fewer errors on letter 4 of stimuli presented entirely in the left visual field (4.6%), than on letter 1 of stimuli presented entirely in the right visual field (31.7%); $\chi^2 = 57.5$; d.f. = 1; $P < 0.001$. This fact cannot be explained by damage to the retina-centred representation.

These results are consistent with the possibility that SVE suffers from a complex deficit. The poorer performance on stimuli presented entirely in the left visual field than on stimuli presented entirely in the right visual field or at the point of fixation suggests mild damage to the retina-centred representation. However, this cannot be the only, nor the main, cause of his dyslexia. He was comparably poor on initial letters, irrespective of absolute location in the visual field; reported the final letters of words presented in the left visual field more accurately than the initial letters of words presented in the right visual field; and, performed very differently on letters that appeared in the same absolute position in the visual field. These facts suggest damage to either the stimulus-centred or the word-centred level of representation. To distinguish between the two possibilities, SVE was asked to read aloud words presented vertically.

Reading aloud four-letter words presented vertically in various absolute positions in the visual field. At the stimulus-centred level, the orientation of a visually presented word is still coded, and letter positions are defined with respect to the centre of the visual material. The stimulus-centred representation of a horizontal word extends to the left and to the right of its centre, whereas the stimulus-centred representation of a vertical word extends above and below its centre. By contrast, at the word-centred level, letter positions are defined with respect to an invariant, canonical representation. At this level, the representation of a word presented horizontally and that of a word presented vertically do not differ. They both consist of a string of graphemes, ordered serially from first to last and from left to right, in which initial letters occupy the same position, irrespective of stimulus location (left of centre, centre, right of centre) and orientation (horizontal, vertical, etc.).

Performance on tasks that require the ability to read

C	C	C
A	A	A
N	●	N
E	E	E

Fig. 3. Absolute position of each letter in four-letter words presented vertically at the three selected locations (centre of locations: 2° of visual angle to the left of the fixation point, at the point of fixation, and 2° of visual angle to the right of fixation). ● = point of fixation (in the experiment, it corresponded to the centre of the computer screen).

aloud a word presented vertically should distinguish between damage to stimulus-centred and word-centred representations. In the former case, words presented vertically should be read flawlessly, or at least with substantially greater accuracy than words presented horizontally. In the latter case, the response accuracy on words presented vertically and on words presented horizontally should be comparable, and errors should involve the same (in our subject, the initial) letters.

The list of four-letter words used for the previous experiment was also used for this experiment. The same time of exposure was selected (250 ms). Words were presented vertically, at one of three locations (the vertical line of fixation, 2° of visual angle to the left or to the right of the vertical line of fixation). The stimuli were centred so that two letters appeared above and two below the point of fixation (Fig. 3). The list was administered twice, over a 1-year period. Overall, SVE was asked to report the same 240 words at each of the three locations, for a total of 720 stimuli.

SVE correctly read aloud 411/720 words (57.1 %). The overall accuracy on this task was indistinguishable from that observed when the same stimuli were presented horizontally (425/720 correct responses, or 59%; $\chi^2 = 0.482$; d.f. = 1; $P = \text{n.s.}$). Our subject correctly produced 110/240 words presented in the left visual field (45.8%), 150/240 words presented at the central location (62.5%), and 151/240 words presented in the right visual field (62.9%).

The response accuracy was significantly lower for stimuli presented in the left visual field than for stimuli presented either at the centre of the visual field ($\chi^2 = 12.764$; d.f. = 1; $P < 0.001$) or in the right visual field ($\chi^2 = 13.436$; d.f. = 1; $P < 0.001$), but it did not differ for the latter two groups of stimuli ($\chi^2 = 0$; d.f. = 1; $P = \text{n.s.}$). Similar results were obtained when the performance on each letter was considered (Table 5). The response accuracy on letters 2, 3 and 4 was significantly lower for words presented in the left visual field than for words presented at the other two locations ($P < 0.001$ in all cases) but it was statistically indistinguishable in stimuli presented centrally and to the right of fixation ($P = \text{n.s.}$ in all cases). These facts establish that SVE suffers from a mild damage to the left half of the retina-centred representation. However, other aspects of his performance point to a different error source: performance on letter 1 was statistically indistinguishable across locations

Table 5. Error rate to each letter in reading four-letter words ($n = 240$) presented vertically in various positions in the visual field. ● = point of fixation (it corresponded to the centre of the computer screen)

Results expressed as a function of the absolute position in the visual field

	Fixation point		
1	42.3	33.8	33.5
2	19.8	7.3	7.3
3	28.5	6.8	4.2
4	14.4	3.5	1.3

Results expressed as a function of the positions in word-centred stimuli

	Word centre			
	x			
	1	2	3	4
Left presentation	42.3	19.8	28.5	14.4
Central presentation	33.8	7.3	6.8	3.5
Right presentation	33.5	7.3	4.2	1.3

and letter 1 was always produced less accurately than letter 2, even when words were flashed along the vertical line of fixation or to the right of the vertical line of fixation (left location: $\chi^2 = 27.4$; d.f. = 1; $P < 0.001$; centre: $\chi^2 = 49.9$; d.f. = 1; $P < 0.001$; right location: $\chi^2 = 49.3$; d.f. = 1; $P < 0.001$). Poor performance on the initial letter of a word, regardless of orientation (horizontal or vertical) and location (entirely in the left or in the right visual field, or at the centre of the visual field), strongly argues for word-centred neglect.

Further evidence for word-centred damage accrues from the comparison of the error types produced in the two tachistoscopic tasks. When reading words presented horizontally, he produced 285 incorrect responses, of which 275 resulted in a word (96.5%), and 10 in a pseudoword (3.5%). Ten stimuli (left: 8/240, or 3.3%; centre: 2/240, or 0.8%) to which he failed to respond were excluded from this analysis. The occurrence of incorrect words in the corpus of interpretable incorrect responses was comparable across stimulus locations (left: 103/106, or 97.2%; centre: 88/94, or 93.6%; right: 84/85, or 98.8%; $\chi^2 = 3.80$; $P = \text{n.s.}$). When reading words presented vertically, SVE produced 291 incorrect responses, that resulted in 286 words (98.3%), and in five pseudowords (1.7%). Also in this case, 18 failures to respond (left: 15/240, or 6.2%; centre: 3/240, or 1.2%) were excluded from the analysis. The occurrence of word responses was comparable across locations (left: 112/115, or 97.4%; centre: 86/87, or 98.9%; right: 88/89, or 98.9%; $\chi^2 = 0.89$; $P = \text{n.s.}$).

The high number of incorrect word responses in these two tasks should be taken cautiously, given the experimental conditions. The stimuli consisted of four-letter words, selected so as to have several orthographic neighbours on the left and SVE had been warned that he would be presented with

words. It is nonetheless interesting that our subject produced comparable numbers of incorrect word responses to horizontal and vertical stimuli (overall: $\chi^2 = 0.025$; $P = \text{n.s.}$), regardless of stimulus location (left presentation: $\chi^2 = 0.660$; $P = \text{n.s.}$; central presentation: $\chi^2 = 0.609$; $P = \text{n.s.}$; right presentation: $\chi^2 = 0.461$; $P = \text{n.s.}$).

That SVE produced identical numbers of correct responses and of incorrect word and pseudoword responses to words presented horizontally and vertically, regardless of the position in the visual field, provides further indirect support for the hypothesis of damage to a location- and orientation-invariant representation.

Writing

On the not unreasonable assumption that spelling and reading rely on the same mechanisms in computing an abstract word-centred representation, spatially specific damage to this level should disrupt spelling as well as reading (Caramazza and Hillis, 1990). And in fact, the inability to spell letters in the contralesional half of the word has been documented in all subjects with word-centred damage (Baxter and Warrington, 1983; Barbut and Gazzaniga, 1987; Caramazza and Hillis, 1990; Hillis and Caramazza, 1995a, b). The hypothesis that our subject suffers from word-centred damage predicts that he should spell initial letters incorrectly.

Because SVE was completely unable to spell orally, only writing tasks were administered. Our subject had no graphomotor problems (he used his unimpaired right hand, which was also his pre-morbidly preferred hand) and wrote very legibly. In the picture naming task ($n = 180$), stimuli were presented for an unlimited time. SVE was asked to respond first orally, then in writing. This procedure was devised because in the event of a written response that substantially deviated from the target, we wanted to have some idea as to the word our subject had tried to produce. In the writing to dictation task ($n = 130$ stimuli, all also used for the picture naming task), each word was presented no more than three consecutive times, but only upon request from our subject. In order to prevent fatigue, these tasks were administered in short sessions (15–20 stimuli per session). SVE was not allowed to correct a written response—if he felt that his output was incorrect, he was asked to write it again from the beginning.

When naming pictures orally, SVE produced 145/180 correct responses (80.6%), 30 semantic substitutions (16.7%), three morphological errors (1.7%) and two anomias (1.1%). Phonemic errors never occurred in this task. In written naming of the same stimuli, he produced only 1/180 correct response (0.6%). Seventy-two (40%) errors involved initial letters only. These letters were omitted in 37 (20.6%) responses (tram → *..am*, pizza → *..zza*; chitarra, guitar → *...arra*; cavallo, horse → *...llo*), and were produced incorrectly in 35, or 19.4% (pera, pear → *fira*; naso, nose → *caso*, case; salame, pastrami → *cirame*). The remaining errors, especially to longer stimuli, were complex or unrelated to the target,

Table 6. Examples of errors in writing that demonstrate selective loss of information on word-initial letters

Omission of initial letters	
Stimulus	Response
Writing to dictation	
tram	<i>..am</i>
gonna, skirt	<i>..nna</i>
cacciavite, screwdriver	<i>...ite</i>
Written naming	
naso, nose	<i>...so</i>
pizza	<i>...zza</i>
motocicletta, motorbike	<i>...tta</i>
Errors on initial letters	
Stimulus	Response
Writing to dictation	
taxi	<i>caxi</i>
gallina, chicken	<i>cillina</i>
baffi, moustache	<i>veffi</i>
lampadario, lamp	<i>ciridari</i>
Written naming	
torta, pie	<i>cirta</i>
barca, boat	<i>circa</i> , almost
occhio, eye	<i>giahio</i>
autobus	<i>boccobus</i>

and often occurred after a correct oral response (autobus → ‘autobus’ → *viogiaus*; pianoforte → ‘pianoforte’ → *cicrostista*). The performance in writing to dictation was comparable, both quantitatively (1/130 correct responses, 0.8%) and qualitatively (54 errors involving initial letters only, or 41.6%), except that fewer responses lacked the initial letter (eight, or 6.2%), and more responses contained one or more incorrect initial letters (46, or 35.4%) than in written naming. Examples of neglect errors are shown in Table 6.

A very low accuracy allowed only a coarse-grained qualitative response analysis in the two writing tasks. Words were divided into two halves, and the number of letters produced correctly in each half was counted. In picture naming, whenever a word was produced that differed from the expected target, SVE’s response was retained for analysis. For example, when he wrote *cacio* for *formaggio* (synonyms for cheese), or *tigre*, tiger for *leone*, lion, *cacio* and *tigre* were scored. Only letters that appeared in the expected order were counted (e.g. in pecora, sheep → *polera*, only the first, the penultimate and the final letter were scored as correct). For words with an odd number of letters, the central letter was ‘split’, and if it had been produced correctly, 0.5 points were credited to both the initial and the final half of that word.

SVE produced comparable numbers of correct letters in written naming (297/1181, or 25.2%) and in writing to dictation (233/856, or 27.2%). In the former task, he correctly produced 32/590.5 letters (5.4%) in the initial half, and 265.5/590.5 letters (45%) in the final half ($\chi^2 = 242.9$; d.f. = 1; $P < 0.001$); in the latter, the corresponding figures

were 34.5/428 (8.1%) and 198.5/428 (46.4%); $\chi^2 = 156.7$; d.f. = 1; $P < 0.001$. The loss of information on initial letters with relative preservation of final letters is fully consistent with previous reports of word-centred damage (Caramazza and Hillis, 1990; Hillis and Caramazza, 1995b)².

Distinct patterns of dysgraphia have been described in subjects with left as opposed to right word-centred neglect. Cases with right-sided neglect (e.g. NG, Caramazza and Hillis, 1990; HB, Hillis and Caramazza, 1995b) were reported to sometimes substitute the final letters of the target with an incorrect, but common letter sequence ('question' → *quester*). In two subjects with left word-centred neglect (ORF, Baxter and Warrington, 1983; ML, Hillis and Caramazza, 1995b), relative sparing of the initial letter was observed ('spider' → *srider*). The latter effect was attributed to sparing of phoneme-grapheme conversion procedures that block the occurrence of unrelated letters and letter sequences in word-initial positions (Hillis and Caramazza, 1995b).

The results obtained by SVE confirm this interpretation. He had produced unrelated or uninterpretable responses to 15 dictated pseudowords, indicating very severe damage to phoneme-grapheme conversion. In the word writing tasks reported here, he correctly produced 16/130 initial letters (12.3%) when writing to dictation and 18/180 (10%) when responding to a picture. The low accuracy on initial letter, and similar performance regardless of whether the stimulus is presented auditorily or as a picture, are both consistent with severe damage to sublexical conversion procedures. Thus, right brain-damaged subjects ORF, ML and SVE offer an interesting contrast. The initial letter was relatively spared in ORF and ML, who presented with partially functional phoneme-grapheme conversion procedures, but it was produced very poorly by SVE, in whom sublexical conversion procedures were essentially abolished. This contrast supports the hypothesis that in left word-centred neglect dysgraphia, accuracy in spelling the initial letter is influenced by the status of phoneme-grapheme conversion procedures.

Discussion

Subject SVE, a corrected left hander, presents with left-sided neglect dyslexia and aphasia following a right hemisphere stroke. He shows very mild neglect in visuo-spatial tasks, and marked neglect in reading and writing. That in tachistoscopic reading tasks he fares significantly worse on four-letter words presented horizontally or vertically to the left of fixation than on similarly oriented stimuli presented to the right of fixation, suggests mild damage to the retina-centred representation. However, the vast majority of his errors in reading and writing are best explained by assuming an impairment at the word-centred level of representation. To begin the discussion of SVE's disorder, we will contrast his performance to that of MR, who suffered from a right hemisphere lesion, and in whom the same tasks documented stimulus-centred damage (Subbiah and Caramazza, 2000).

Both SVE and MR were asked to read a set of five-letter

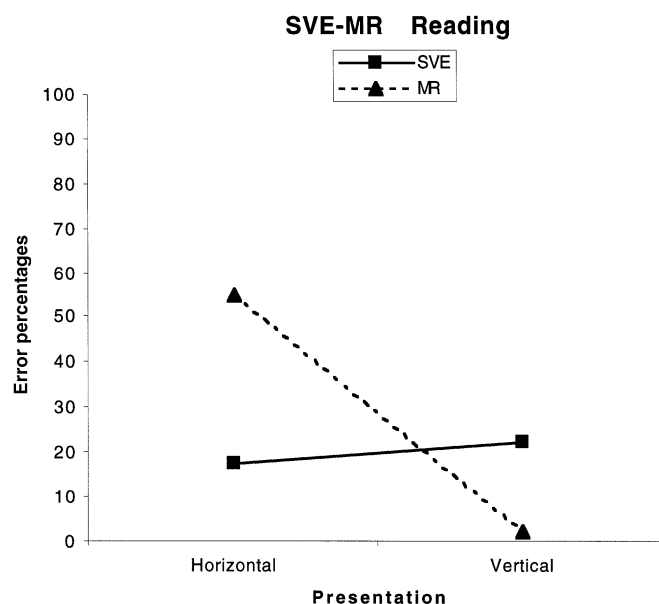


Fig. 4. Comparison of subjects SVE and MR (Subbiah and Caramazza, 2000). Tachistoscopic reading of four-letter words presented horizontally (SVE and MR) and vertically (SVE) at various positions in the visual field: occurrence of incorrect responses to letters in various positions.

words presented horizontally and vertically without time constraints (Fig. 4). In the horizontal task, MR, who incorrectly read aloud 22/40 words, or 55%, fared much worse than SVE, who incorrectly read aloud 8/45 stimuli, or 17.7% ($\chi^2 = 11.269$; d.f. = 1; $P < 0.001$). When the same words were presented vertically, the performance of the two subjects still diverged, but in the opposite direction. SVE produced a number of incorrect responses similar to that observed in the previous task (10/45, or 22.2%), whereas MR performed almost flawlessly (1/40, or 2.5%; $\chi^2 = 5.665$; d.f. = 1; $P < 0.02$). The two subjects also showed contrasting patterns in writing. MR omitted strokes and omitted or perseverated letters across all positions in the target string (Subbiah and Caramazza, personal communication), whereas SVE omitted or incorrectly produced word-initial letters, but never perseverated letters, nor produced ill-formed letters.

Both SVE and MR are clinically classifiable as neglect dyslexics, but their performance in reading and writing shows marked contrasts. To be reliable, any theory of neglect must provide a coherent account for these contrasts. Within the framework proposed by Caramazza and Hillis (1990), the disorders observed in these two subjects find reasonably straightforward accounts. Subject MR suffers from damage to a representational level that specifies a string of letter shapes in a coordinate frame centred on the stimulus and defined by its spatial envelope (the stimulus-centred representation). Thus, he incorrectly reads initial letters in words presented horizontally, regardless of their absolute position in the visual field, but makes no errors in reading the same words when presented vertically. Subject SVE presents with a difficulty in computing the contralesional half of an abstract representation, invariant with respect to the physical properties of the stimulus, and comprising a

spatially arranged sequence of abstract letter identities (the word-centred representation). As a consequence, he produces comparable numbers of errors at word beginnings in reading, irrespective of absolute position in the visual field (just like MR), but also regardless of orientation (contrary to MR) and makes similar word-initial errors in writing (also contrary to MR). We will now consider alternative interpretations, to see if they provide a convincing account of the pattern of performance documented for SVE.

Could SVE's dyslexia result from a positional (as opposed to a visuo-spatial) deficit?

A pattern of dyslexia and dysgraphia similar to that reported for SVE, but affecting the right side of words (subject DES), was attributed to a positional deficit by Greenwald and Berndt (1999). These authors propose that a difficulty in reading and spelling letters in the contralesional half of a word can result from damage to distinct mechanisms, depending on the hemispheric side of the lesion. A visual-spatial deficit causes the disorder observed in subjects with right hemisphere damage (e.g. Baxter and Warrington, 1983; Barbut and Gazzaniga, 1987) and in some cases with left hemisphere damage (e.g. Caramazza and Hillis, 1990), whereas the reading deficit observed in DES and other subjects with left hemisphere lesions might be determined by damage to a mechanism responsible for ordering the letters in the written string. In these subjects, an interaction of positional damage with an intrinsic bias favouring initial elements in orthographic representations (suggested by fixation time experiments; Lima, 1993), or with sparing of grapheme-phoneme conversion procedures (Peressotti and Grainger, 1995), or with a letter-by-letter reading strategy (DES was a letter-by-letter reader), would result in the selective sparing of word-initial letters, and the loss of information on final letters. Because this pattern can only occur following left hemisphere damage, the positional deficit hypothesis does not apply to SVE, who produced stimulus-initial errors after right brain damage. An account of the performance observed in this subject must be formulated in terms of damage to visuo-spatial mechanisms.

Is it possible to account for the disorder observed in SVE without assuming damage to the word-centred representation, or without assuming that a word-centred representation is computed in reading?

We have argued previously that SVE's reading and writing disorder is best accounted for by assuming damage to a spatially defined, word-centred representation, in the context of a multiple-stage model of word recognition. Before deeming this conclusion appropriate, we consider other visuo-spatial damage hypotheses as they may apply to our subject.

A first possibility is to accommodate his reading performance in the same theoretical framework, but without assuming word-centred damage. One might hypothesize that several lower-level impairments independently cause errors on initial letters in horizontal and vertical presentation. In reading horizontal words, left retina-centred damage might yield errors on letters in the contralesional hemifield and left stimulus-centred damage might yield errors on initial letters regardless of absolute stimulus location. In reading words presented vertically, altitudinal (retina- or stimulus-centred) neglect for the upper half of the visual field might cause word-initial errors. This account is biologically implausible in a subject with a unilateral lesion, like SVE. There are no reports of bilateral vertical neglect following a unilateral lesion and the few cases with bilateral lesions suffered from neglect for the lower half of the visual field (e.g. Rapcsak *et al.*, 1988; Butter *et al.*, 1989; Nichelli *et al.*, 1993). This account is also functionally implausible, as our subject showed no signs of altitudinal neglect in purely visual tasks. Furthermore, the rich constellation of deficits considered here still fails to accommodate SVE's spatially specific dysgraphia. (Of course, it could be assumed that the reading and the writing disorder result from distinct impairments, but this account would be even more cumbersome.) Thus, word-centred damage associated with mild retina-centred damage most naturally and parsimoniously accounts for the overall pattern of performance observed in our subject³.

So far, we have discussed SVE's performance in the context of multiple-stage models, that assume distinct retina-, stimulus- and word-centred levels of representation. However, it has been claimed that the patterns of performance observed in subjects with neglect dyslexia do not require the assumption that a word-centred representation is computed in reading. We will now evaluate SVE's performance in this alternative framework.

The most explicit proposal of this type is MORSEL (Mozer, 1987, 1988), a computational model of attention used by Mozer and Behrmann (1990) to explain the phenomena observed in subjects with neglect. In MORSEL, neglect results from damage to the connections from the model's retina to the model's attentional system. Such damage is graded⁴ and, in a subject with a right hemisphere lesion, it increases from right to left. In addition, there is lateral inhibition among the adjacent elements of a visual representation, and the strength of the inhibition is modulated by the gradient of deficit. Consequently, a right-to-left gradient of damage will result in each element receiving stronger inhibitory links from elements to its right than to its left. In the case of left neglect dyslexia, each letter in a word presented canonically (i.e. written horizontally from left to right) will receive greater interference from letters to its right than to its left. Under these assumptions, damage to one level of representation will result in both absolute and relative left-sided neglect. In retinal space, letters on the left will be produced less accurately than those on the right; in stimulus space, letters on the left will be produced less accurately

than those on the right, regardless of their position in retinal space. The pattern reported for SVE is broadly consistent with these predictions. However, a closer analysis of the data yields a much less satisfactory fit to the model. Two comparisons are relevant: the contrast between the performance on letter 1 of words presented at the centre of the visual field and on letter 3 of words presented to the left of fixation, and that between the performance on letter 1 of words presented to the right of fixation and on letter 3 of words presented at the centre of the visual field. Letters in each pair appear at the same location in retinal space and are flanked by a letter to their right. Thus, according to MORSEL, they should be produced with similar accuracy. As already shown in Table 4, this is not the case, as SVE produced significantly fewer correct responses to letter 1 of words presented centrally than to letter 3 of words presented in the left retinal space ($\chi^2 = 48.1$; $P < 0.001$), and to letter 1 of words presented in the right retinal space than to letter 3 of words presented centrally ($\chi^2 = 68.7$; $P < 0.001$)⁵. Thus, MORSEL cannot account for SVE's performance in reading words presented horizontally. In addition, it allegedly cannot accommodate the spatially specific errors in reading vertical words and in spelling, as it was developed to account only for neglect occurring in a viewer-centred frame of reference (Mozer and Behrmann, 1990, p. 102).

In a somewhat similar vein, Farah *et al.* (1990) and Buxbaum *et al.* (1996) do not assume an object-centred representation, and maintain that the phenomena observed in apparent object-centred neglect can be accounted for by task-induced mental rotation. Taking this view, the errors produced by SVE when reading words presented horizontally would be accounted for by graded neglect resulting from damage to left retinal and stimulus space (as in MORSEL). Errors in reading the same words when presented vertically would be determined by a task-induced rotation strategy. Because each word, rotated anticlockwise by 90°, would be placed in a stimulus-centred frame of reference, words presented vertically would yield exactly the same errors as words presented horizontally. This account falls short of explaining SVE's behaviour. Rotating a word presented as in Fig. 3 does not yield a 'canonical' abstract letter representation, as each element of the string still has to be rotated clockwise by 90°—it is not clear why a subject would engage in such an ineffective strategy when reading vertical words. In this framework, the weaker assumption that, irrespective of whether or not stimulus rotation occurs, vertical reading is accomplished by a more serial strategy than horizontal reading cannot accommodate the observed pattern of performance. The notion that reading a vertical word requires serially placing letters in a left-to-right oriented, viewer-centred representation does not explain why only word-initial letters are affected in SVE and only word-final letters in other subjects like NG, short of positing a spatially coded, word-centred representational level.

In summary, only theories assuming that distinct levels of representation are computed during word recognition, and

that one of these levels has the properties of a word-centred representation (Caramazza and Hillis, 1990; Haywood and Coltheart, 2000; see also Monk, 1985) or of a three-dimensional model representation (Marr, 1982) can account for the full range of phenomena reported in subjects with neglect dyslexia.

The discrepancy between neglect in reading/writing and neglect in other visual-spatial tasks

In cases of retina- and stimulus-centred deficits, neglect dyslexia is always correlated with a clear visual neglect (but, see Haywood and Coltheart, 2000 for a different position). By contrast, this correlation is much looser in subjects with word-centred damage. Clinical signs of visual neglect are obvious in some subjects (e.g. Caramazza and Hillis, 1990), but very mild in others (e.g. HB, Hillis and Caramazza, 1995b). The latter is the case in SVE, who presented with severe neglect dyslexia, but showed only minor neglect in purely visual tasks. This discrepancy deserves a short comment.

It would be tempting to use the data from subjects like HB and SVE to argue that object recognition and word recognition share retina-centred and stimulus-centred representations, whereas they require distinct computations at a location-, size- and orientation-invariant level (an object-centred and a word-centred representation, respectively). However, different performance levels in reading and in purely visual tasks might simply result from the fact that the two types of tasks pose different computational requirements (Hillis and Caramazza, 1995b). For example, a strategy based on successive eye fixations will help performance on purely visual tasks (e.g. search or cancellation), in which each line or symbol can be treated like a separate object, but not on reading tasks, in which an object with a complex graphemic structure, extending into the left half of the representation must be processed. This would result in more obvious clinical manifestations of neglect dyslexia than of visual neglect. In the subject reported here, other factors might have contributed to the observed discrepancy. After his stroke, SVE took up painting—he paints everyday, but seldom reads and essentially never writes. Perhaps, daily practice on visual-spatial tasks and the lack of similar practice in reading and writing may have induced compensatory strategies for visual neglect, but not for neglect dyslexia/dysgraphia. Also, most reading tasks were administered tachistoscopically, whereas most visual tasks were administered without time constraints. In summary, the discrepancy between marked neglect dyslexia and mild visual neglect is still consistent with damage to a spatially determined, word-centred representation, shared by word and object recognition processes.

The implications of available reports of word-centred neglect dyslexia for brain/behaviour relationships

Retina- and stimulus-centred neglect have been frequently and consistently reported in right-handed subjects with damage to

Table 7. Hand preference, hemispheric side and site of lesion, presence/absence of aphasia and clinical signs of neglect in subjects with neglect dyslexia resulting from probable damage to the word-centred representational level. DES (Greenwald and Berndt, 1999) is not included, as he may not have suffered from visuo-spatial deficit. He is a right hander with a left hemispheric lesion

Case	Sex Aphasia	Hand preference	Lesion side Neglect in visual-spatial tasks	Lesion site
ORF ^a	M Mild anomia	Left	Right ?g	Parietal; posterior temporal
ML ^b	F Agrammatic	Left	Right Y	Fronto-parietal with basal ganglia
JL ^c	M Anomia, conduction aphasia	Corrected left hander	Right Y	Parietal
SVE	M Agrammatic	Corrected left hander	Right Very mild	Frontal, parietal and temporal with basal ganglia
NG ^d	F None	Corrected left hander	Left Y	Parietal lobe; caudate nucleus
HB ^b	M Semantic	Right	Left Only in tactile search	Fronto-parietal
RYT ^e	M Mild naming disorder	Right	Left Not on clinical tasks	N/A
HH ^f	M Mild, fluent	Right	Left Not on clinical tasks	Medial-post-temporal; occipital; thalamus

^aBaxter and Warrington (1983).^bHillis and Caramazza (1995b).^cBarbut and Gazzaniga (1987).^dCaramazza and Hillis (1990).^eWarrington (1991).^fHillis and Caramazza (1990).^gORF had two strokes; no neglect was reported after the first stroke.

the posterior regions of the right hemisphere. By contrast, observations of word-centred neglect dyslexia constitute a riddle from the viewpoint of brain/behaviour correlates. The disorder has only been reported in very few subjects (Table 7) whose lesions usually involve the parietal lobe, but frequently extend to the frontal lobe. The most puzzling observation is that many subjects with word-centred neglect dyslexia show anomalous relationships between hand preference and hemispheric dominance for language. There are reports of left handers with damage to the left hemisphere (Caramazza and Hillis, 1990) and to the right hemisphere (Baxter and Warrington, 1983; Barbut and Gazzaniga, 1987; Hillis and Caramazza, 1995b) and of right handers with lesions to the left hemisphere (Hillis and Caramazza, 1990, 1995b; Warrington, 1991). However, there are no reports of right handers with damage to the right hemisphere. Thus, proposals on the anatomo-clinical correlates of word-centred representations must account for the paucity of reports, and for the frequent occurrence, among them, of subjects with unusual relationships between hand preference and brain dominance.

These two facts about word-centred neglect dyslexia may be seen as two faces of the same coin—the disorder has been reported infrequently because it is more easily revealed in subjects with unusual neural implementations of cognitive functions. Perhaps, there are no reports of right handers with right hemispheric lesions in this small group of subjects because word-centred representations are usually computed in regions that either overlap or are contiguous with other regions representing functions which, when damaged, mask

the occurrence of word-centred neglect (or prevent its empirical investigation). Thus, only when word-centred representations and the other relevant functions segregate in distinct brain regions is it possible to observe word-centred neglect dyslexia. If this is the case, a biologically viable account of the anatomo-clinical correlates of word-centred representations requires an explanation both for the arrangement that normally results in the inability to demonstrate word-centred neglect, and for the modifications to that arrangement which result in this form of neglect dyslexia being often reported in subjects with uncommon relationships between hand preference and hemispheric dominance for language. (Note that the ‘anomaly’ of these subjects only concerns the localization of cognitive functions in their brain, and not the functional organization of their cognitive system.)

One possibility is that in right handers with left dominance for language all three levels of representation involved in word recognition are usually implemented in the right hemisphere. On this account, failure to report word-centred neglect following right hemisphere lesions would result from the frequent co-occurrence of retina- and stimulus-centred damage, which might mask word-centred damage. In rare cases, the three levels are disaggregated, and the word-centred representation is implemented separately (probably, retina- and stimulus-centred representations would still be computed in the right hemisphere, whereas word-centred representations would be computed in the left hemisphere). In these subjects, selective damage to the word-centred representation would become visible after left hemispheric lesions, frequently associated with aphasia. Taking this view,

the extant lack of reports of word-centred neglect dyslexia following right hemisphere damage in right handers is all the more conspicuous, as it would result essentially from insufficiently accurate neuropsychological analyses. This sounds implausible, considering the interest that neglect dyslexia has aroused in the past few years. However, this account is the most easily tested—if true, an increasing number of right handers with word-centred damage following right hemisphere lesions will be reported in the near future.

An alternative possibility is that normally the retina- and stimulus-centred representations are computed in the right hemisphere and the word-centred representation in both hemispheres (Hillis and Caramazza, 1995a). On this account, each hemisphere is mostly equipped to attend to the contralateral half of the word-centred representation, but also to some extent to its ipsilesional half. This would be possible, for example, if each hemisphere contained neural units devoted to processing both sides of the representation, but contained more units for the contralateral as compared with the ipsilateral side. In the event of unilateral damage, the intact hemisphere would still be able to process the contralesional half of the graphemic representation, resulting in relatively accurate performance, at least in untimed tasks. Consequently, word-centred neglect dyslexia would only be detected in these subjects by very demanding tasks (e.g. tachistoscopic reading), infrequently used in clinical practice. In some subjects, however, the computation of word-centred representations could be strongly lateralized, and each hemisphere would be almost exclusively responsible for computing the contralateral half of the word-centred representation. In these subjects (and, only in these subjects), hemispheric damage would result in obvious contralesional word-centred neglect. Like the hypothesis considered in the previous paragraph, this account predicts the yet unreported occurrence of word-centred neglect in right handers following right hemisphere damage.

Still another possibility is that in right handers the word-centred representation is usually computed in the left hemisphere. In this case, the rarity of word-centred neglect dyslexia might be due to the very frequent co-occurrence of word-centred damage and aphasia, which would render the disorder not amenable to empirical investigation in most subjects. Taking this view, only a disaggregation (at least partial) of the mechanisms that compute word-centred representations from those involved in other aspects of language could make word-centred neglect both conspicuous and testable. This might happen if language functions and the word-centred representation were processed either bilaterally or in separate hemispheres [this was probably the case in NG (Caramazza and Hillis, 1990), who had severe word-centred dyslexia without aphasia]. This hypothesis receives some support from the observation that the only cases of word-centred neglect dyslexia in right handers occurred after left brain damage (HB, Hillis and Caramazza, 1995a; HH, Hillis and Caramazza, 1995b; RYT, Warrington, 1991).

Acknowledgements

The authors wish to thank SVE and his family for their cheerful and constructive participation in this project. We also wish to thank Dr Patrizia D'Erme for referring the subject, Alfonso Caramazza for discussions on previous versions of the manuscript, and three anonymous reviewers for their helpful suggestions. Preparation of this manuscript was supported in part by grants from MURST and from NIH grant NS34073.

Notes

¹ Because this representational level is shared by familiar and novel words, a more appropriate name for the information computed at this stage of the reading process would be 'abstract letter string-centred' representation. However, it is still debated whether this level is specific for written words, or is shared by word and object recognition processes. In this case, 'object-centred' representation would be a more appropriate label. In the light of the current uncertainty on this issue, and of the fact that the data collected from SVE almost exclusively concern words, both in reading and writing, we will use the (albeit unsatisfactory) term 'word-centred' to refer to this level of representation.

² This pattern differs strikingly from that reported in subjects with stimulus-centred neglect (e.g. Ellis *et al.*, 1987b), whose errors resulted in letter perseverations, stroke omissions and perseverations, occurring in all within-word positions. SVE never produced these errors.

³ We have not drawn explicit conclusions on the status of the stimulus-centred level in this subject. It is very difficult to obtain direct evidence on the status of this representational level in the presence of concomitant retina- and word-centred damage, as an impairment of these two levels might mask stimulus-centred damage. However, some aspects of SVE's performance suggest that the stimulus-centred representation is largely spared. In writing, he showed the behaviour documented for other subjects with word-centred damage, but never produced the types of errors observed in subjects with stimulus-centred damage. In addition, a contrast between severe neglect dyslexia and dysgraphia and very mild visual neglect is observed in subjects with word-centred neglect, but not in subjects with stimulus-centred neglect, in whom the two disorders are of comparable severity (Hillis and Caramazza, 1995b; for a different view, see Haywood and Coltheart, 2000). It is also worth stressing that no aspects of this subject's performance require the assumption of stimulus-centred damage.

⁴ This property is not unique to computational models. Damage to the retina-, stimulus- and word-centred representation can also result in a graded deficit in multiple-stage models (Hillis and Caramazza, 1995a). One needs only assume that at each representational level the number/density of neurones that compute the target representation in each

hemisphere is highest for the extreme contralateral half, and gradually decreases moving towards the ipsilateral half.

⁵The same procedure was used in the analysis of the reading performance of subject MR, who suffered from stimulus-centred damage (Subbiah and Caramazza, 2000). Also in that study, reading performance did not fit the predictions of MORSEL.

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Received on 20 January, 2000; resubmitted on 1 September, 2000; accepted on 4 September, 2000

Word-centred neglect dyslexia: evidence from a new case

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Abstract

Neglect dyslexia resulting from damage to word-centred representations is extremely rare. We report on a new case. A left-handed subject, SVE, presented with aphasia and neglect dyslexia/dysgraphia following a right hemisphere stroke. In tachistoscopic reading tasks, some of his errors resulted from retina-centred neglect, as he responded more accurately to words flashed in the left visual field than to words flashed in the right visual field. However, the critical aspects of his reading performance indicated word-centred neglect. SVE incorrectly produced the initial elements of four-letter words, regardless of stimulus location (to the left and to the right of fixation, or at fixation), and orientation (horizontal and vertical presentation). A similar distribution of errors was demonstrated in writing (very inaccurate performance on initial letters). This pattern of performance suggests damage to an abstract letter string representation defined by spatial coordinates, rather than to an ordering mechanism. It is most naturally accommodated by models of word recognition which assume a word-centred level of representation, and cannot be explained by models which do not include such a representational level. Consideration of our subject in the light of other similar reports prompts hypotheses on the neural mechanisms involved in computing word-centred representations.

Journal

Neurocase 2001; 7: 221–37

Neurocase Reference Number:

O219

Primary diagnosis of interest

Neglect dyslexia in a corrected left hander

Author's designation of case

SVE

Key theoretical issue

- Damage to word-centred representation

Key words: neglect dyslexia; neglect dysgraphia; models; anatomo-clinical correlates of visual word recognition

Scan, EEG and related measures

MRI

Standardized assessment

Batteria per l'Analisi dei Deficit Afasici (BADA)

Other assessment

Reading, writing, visual–spatial tasks

Lesion location

- Right frontal–parietal

Lesion type

Ischaemic

Language

Italian