Reprinted from Nature, Vol. 346, No. 6281, pp. 267–269, 19th July, 1990

Spatial representation of words in the brain implied by studies of a unilateral neglect patient

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READING and writing require access to stored knowledge about the spelling of words. Presumably, we recognize *chair* but not *chare* or *chiar* as a word of English, and similarly would write 'chair' but not 'chare' or 'chiar', because we access orthographic representations that specify the identity and the order of the graphemes (abstract letter representations) that comprise the spelling of words[1,2]. Thus, a fundamental problem concerns the content and structure of the hypothesized orthographic representations, and how information about grapheme order is represented and processed. We present evidence from a brain-damaged patient (N.G.) with unilateral neglect that this information is coded spatially. Unilateral neglect is a disorder clinically characterized by the inability to perceive or respond to stimuli presented to the side contralateral to the site of lesion, despite the absence of significant sensory or motor deficits[3,4]. The patient made reading and spelling errors only on the right half of words, regardless of length. Furthermore, she produced the same pattern of errors in reading and spelling, irrespective of the topographic arrangement of stimuli in reading (horizontal, vertical or mirror-reversed words) and of the type of response in spelling (written, oral or backward oral spelling). This pattern of performance suggests that order information in orthographic representations is coded spatially in a word-centred coordinate system; that is, in a spatially defined coordinate frame whose centre corresponds to the midpoint of a canonical, orientation-invariant representation of the word and not the midpoint of the word stimulus[5].

N.G. is a 77-year-old left-handed woman, who presented with a particularly pure clinical picture of unilateral neglect due to a stroke involving a large area of the left parietal white matter and the left anterior basal ganglia, adjacent to the head of the caudate nucleus (as revealed by CT scan). In contrast to her normal spoken language, eye movements and visual fields, N.G. showed severe difficulties in processing the right side of objects and words: in bisecting lines she systematically displaced the centre to the left; in drawing objects from memory she omitted or distorted details on the right side; and in reading and writing she made errors only on the right side of words. The right-sided reading errors persisted even when it could be demonstrated that she had processed the whole word, as revealed by her flawless ability to name all the letters in the word. Similarly, her bisection displacement persisted even after she successfully indicated the extremities of the line before bisecting it (see Fig. 1). Thus, N.G.'s unilateral neglect seemed to reflect a deficit in processing the right side of internal representations and not a deficit in sensory processing or stimulus scanning[6–13].

N.G. was asked to read and write several thousand words of various lengths in various tasks ($n = 2,202$ and 1,662, respectively). The stimuli used in the various tasks were selected from word lists controlled for standard lexical and non-lexical factors known to affect reading and spelling performance, such as word and stem frequency, grammatical class, length, concreteness, and morphological structure. The lists were compiled from The Johns Hopkins Dyslexia and Morphology Batteries. Overall accuracy was 77% in reading and 24% in spelling. The only factor to affect performance in reading was frequency—N.G. read high-frequency words with greater accuracy than low-frequency words. The only factor to affect spelling was length, as she spelled short words with greater accuracy than long words. Furthermore, errors were only made on the right half of a word, and these increased linearly as a function of absolute distance in graphemes from the centre of the word (Table 1). This result was independent of the form of stimulus input in reading and the form of output in spelling, that is, N.G. produced virtually identical rates and distributions of errors in reading words presented in horizontal, vertical or mirror reversed form. She also produced essentially identical rates and distributions of errors in written, oral and backward-oral spelling of words. The distribution of errors as a function of letter position in a word was virtually identical across all reading and spelling tasks (Table 2). Examples of N.G.'s performance in the various reading and spelling tasks are shown in Fig. 1. In all tasks, her errors were restricted to the 'right' end of canonical representations of words.

Although other brain-damaged subjects have been described whose reading performance is similar to that of N.G.[6,9,10,12,13], none of these showed a spatially-specific deficit which (where tested) remained invariant—always involved the same end of the word—under topographic transformations of the stimulus (horizontal, vertical and mirror-reversed orientation). Thus, N.G. read the horizontally presented word *hound* as 'house' and the mirror-reversed word *common* as 'comet'. These errors involve the ends of words, despite the fact that their relative positions in the stimuli are on the right and left part of the stimuli, respectively. This pattern of performance contrasts with that of similar patients previously described. For example, patient V.B.[12] made errors on the left part of word stimuli—the beginnings of words—when they were presented in normal, horizontal orientation, and continued to make errors on the left part of word stimuli—the ends of words—when they were presented in mirror-reversed form. These errors involve the same relative position in the stimulus word and not the same position within a canonical, orientation-invariant representation of the word, as with N.G.

The contrasting results obtained for N.G. and V.B. and other patients with different forms of neglect dyslexia, provide evidence for a dissociation between different levels of representation in visual word recognition, that is between a canoni-

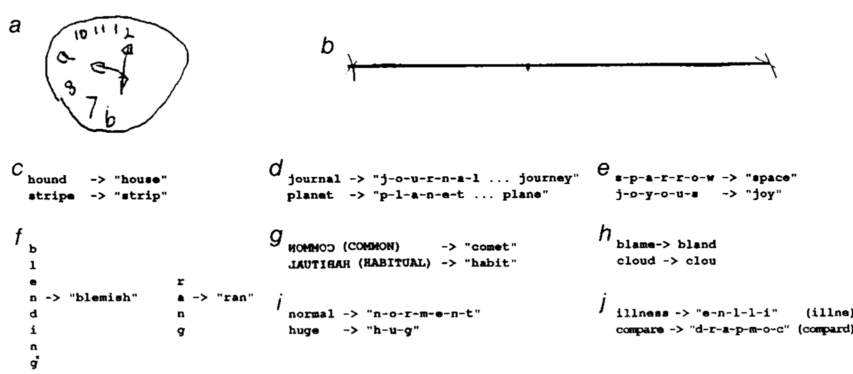

FIG. 1 Examples of N.G.'s performance in various tasks. *a*, Attempt to draw a clock; *b* bisection of a 5-inch line after having indicated the extremities. The centre is shifted to the left, indicating neglect of the right end of the line; *c*, reading horizontally displayed words; *d*, reading horizontally displayed words after naming the letters in the words; *e*, naming orally spelled words; *f*, reading vertically displayed words; *g*, reading mirror-reversed words; *h*, written spelling; *i*, oral spelling; *j*, backward oral spelling. Note that in all cases errors only involved the right half of a canonical, word-centred representation of the word, and not the right half of a viewer-centred representation (compare horizontal and vertical, and mirror-reversed conditions in reading) or the last letters produced (compare oral and backward oral spelling).

TABLE 1 Distribution of errors as a function of letter position in words of different lengths

Reading — Position in word

Word length	1	2	3	4	5	6	7	8	9
4 (141)	0	0	4	15					
5 (219)	0	0	1	8	18				
6 (204)	0	0	0	4	8	25			
7 (82)	0	0	1	4	5	16	31		
8 (88)	0	0	0	1	3	18	21	34	
9 (55)	0	0	0	0	2	10	23	28	37

Spelling — Position in word

Word length	1	2	3	4	5	6	7
4 (48)	0	2	13	25			
5 (70)	0	0	6	20	29		
6 (62)	0	0	5	15	26	39	
7 (67)	0	0	3	5	15	28	51

Reading — Word Centre

Word length									×								
4						0		0		4		15					
5					0		0		1		8		18				
6				0		0		0		4		8		25			
7			0		0		1		4		5		16		31		
8		0		0		0		1		3		18		21		34	
9	0		0		0		0		2		10		23		28		37

Spelling — Word Centre

Word length							×						
4				0		2		13		25			
5			0		0		6		20		29		
6		0		0		5		15		26		39	
7	0		0		3		5		15		28		51

The top part of each panel reports percentage errors at each letter position for 4- to 9-letter words in reading and 4- to 7-letter words in writing to dictation. The number of stimuli for each word length is shown in parentheses. The bottom of each panel reports the same data, with each word length arranged by reference to the centre of words. When performance is displayed in the latter fashion, it is apparent that reading and spelling errors occur almost exclusively on the right half of words, and increase linearly as a function of absolute distance in number of graphemes from the centre of the word.

TABLE 2 Distribution of errors as a function of letter position

Task	Letter position in 6-letter words (% of total errors) 1	2	3	4	5	6
Regular reading	0	0	0	9	27	64
Vertical reading	0	0	2	10	35	52
Naming of orally spelled words	0	0	7	20	28	45
Mirror-reversed reading	0	1	9	16	29	46
Written spelling	0	0	6	19	31	46
Oral spelling	0	1	2	7	29	60
Backward spelling	0	0	1	12	34	53
Delayed copying	0	1	1	13	28	57

Percentage errors are reported for each letter position for the same set of 6-letter words ($n=108$) used in all reading and spelling tasks. The results show that errors are virtually restricted to the right half of each word, independently of the form of input in reading (horizontal, vertical or mirror-reversed written words or orally spelled words) and independently of the type (written or oral) and order (forward or backward) of output in spelling.

TABLE 3 Percentage correct stem responses

Stimulus type	n	% Correctly read stem
Unaffixed stem	96	75%
Legally suffixed stem ($\chi^2(1)=15.10$, $P<0.001$)	96	96%
Unaffixed stem	287	66%
Illegally suffixed stem ($\chi^2(1)=61.23$, $P<0.001$)	287	93%

Percentage correct stem responses for 'legally' suffixed words, 'illegally' suffixed words and the same stems without suffixes. Responses were scored as correct if the entire stem was produced (whether or not the suffix was read correctly). It was hypothesized that NG would correctly read the stem more often when a suffix was added, because a greater number of letters would be on the left half of the representation. For example, only 'lau' occurs on the left half of launch (which N.G. read as 'laundry'), where 'laun' (and half of c) occur on the left half of the illegally suffixed form, 'launchify' (which she read as 'launcher'). Generally, N.G.'s responses retained at least the left half of the stimulus: for example, she read 'child' as 'chill' but read its legally suffixed form, 'childishly' as 'childless'.

cal, word-centred representation and a stimulus- or viewer-centred representation of word stimuli[5]. N.G.'s performance contrasts with previously reported cases in that her spelling performance was qualitatively identical to her performance in reading, and was invariant for different forms of output (written or oral spelling, forward or backward spelling). These results severely constrain hypotheses about the nature of the deficit responsible for N.G.'s reading and spelling performance:

(1) The fact that N.G.'s reading impairment took the same form irrespective of topographic transformations of the stimulus input (such as, normal compared with mirror-reversed presentation), rules out the possibility that the deficit involves levels of representation where information is arrayed retinotopically or in a viewer-centred coordinate system[12]. Instead, this fact implies that the deficit involves a level of processing where graphemic information is represented in an orientation-invariant canonical form, that is, in a word-centred coordinate system.

(2) The fact that her spelling deficit took the same form irrespective of whether a written or oral response was required, and that her performance remained invariant regardless of the order of output (forward or backward spelling)[9], rules out a deficit to a serial order processing mechanism as well as a deficit to premotor mechanisms for planning actions in space. Oral spelling does not involve planning actions in external space, yet errors were restricted to the right half of words.

(3) Because N.G.'s processing difficulties took the same form in reading and spelling, irrespective of the stimulus input or form of response, the deficit seems to concern a level of representation that has abstracted away from the specifics of the two sets of tasks. The deficit may concern a level of processing that specifies the identity and order of abstract letter representations and not one that encodes specific letter shapes.

(4) The points in (1) and the fact that N.G.'s reading and spelling processing deficit was restricted to the right end of words regardless of the form of input or output suggests that her difficulty involves processing the right part of a canonical orthographic representation in a word-centred coordinate system.

Facts (1)–(4), and the fact that reading peformance remained invariant for normal and mirror-reversed words, and that reading and spelling performance were qualitatively identical, suggest that reading and spelling involve computing a spatially coded, abstract orthographic representation in a word-centred coordinate system. For N.G., it would be expected that adding letters on the right end of a word should facilitate its reading because the centre of the internal representation of the longer graphemic string would be shifted rightward with the consequence that a greater part of the word falls in the left, normally processed half of the representation. For example, N.G. should be much more likely to produce the stem 'contrast' (with or without a suffix) when shown *contrastiveness* than when shown *contrast.* She might read *contrastiveness* as '**contrast**ing' or '**contrast**ive', but in reading *constrast* she should produce responses such as '**con**tinue' or '**con**trol'. In several experiments, this expectation was fully supported, as she made significantly fewer reading errors on the stems of suffixed words (e.g. *harassment*) than unaffixed words (e.g., *harass*) (Table 3).

The task-independent but highly specific form of reading and writing deficit shows that one form of unilateral neglect results from a selective deficit in processing the right (or left) half of abstract, orientation-invariant, internal representations. This indicates that the order of graphemes in an`orthographic representation is coded by reference to relative spatial positions in a word-centred coordinate system. □

Received 4 April; accepted 18 May 1990.

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ACKNOWLEDGEMENTS. We thank N.G. for her participation in the study, and M. McCloskey, B. Rapp and S. Yantis for helpful comments on the paper. This work was supported by grants from the NIH, the Seaver Institute and the McDonnell-Pew Program in cognitive neuroscience.