

## Dissociable Coordinate Frames of Unilateral Spatial Neglect: “Viewer-Centered” Neglect

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Detailed analyses of reading and nonlexical tasks by three patients with unilateral spatial neglect (USN) secondary to stroke indicate that the USN in each of these patients affects the left side (contralateral to brain damage) of the viewer, with respect to the viewer's head, mid-sagittal plane of the body, or line of sight. In one case, the neglect was further specified as concerning the left side of the viewer's line of sight (the left half of her residual visual field). Thus, the frame of reference of USN in these three cases appears to have viewer-centered (in at least one case, specifically retinotopic) coordinates. The performance of these patients is contrasted to that of other patients in the literature whose USN appears to have a frame of reference with stimulus-centered or object-centered coordinates. These results are interpreted within a model of visual processing (adapted from Marr, 1980 and others) with at least three coordinate frames. It is argued that USN can affect one or more of these coordinate frames independently. © 1998 Academic Press

Unilateral spatial neglect (USN) is a disorder characterized by the failure to acknowledge or respond to stimuli on the side of space contralateral to

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the hemisphere of brain damage. Research with neurologically impaired patients and experimentally lesioned animals has shown that USN can affect processing in different spatial coordinate frames: USN can affect processing of information on one side of the visual field, the head, or the body contralateral to brain damage (Bisiach, Capitani, & Porta, 1985; Calvanio, Petrone, & Levine, 1987; Karnath, Schenkel, & Fischer, 1991; Ladavas, 1987), but also the side of the stimulus contralateral to brain damage, irrespective of its location in the visual field or body (Behrmann & Moscovitch, 1994; Behrmann & Tipper, 1994; Buxbaum & Coslett, 1994; Caramazza & Hillis, 1990a; Chatterjee, 1994; Driver & Halligan, 1991; Driver, Baylis, Goodrich, & Rafal, 1994; Hillis & Caramazza, 1995a, b; Moscovitch & Behrmann, 1994; Tipper & Behrmann, 1996; see also Mennemeier, Chatterjee, & Heilman, 1994, for a similar claim). One implication of the existence of different patterns of USN is that visual processing involves distinct representational levels with different spatial coordinate frames. Although this proposal enjoys wide acceptance, there continues to be disagreement regarding (1) the number and characterization of the different coordinate frames and (2) whether there are separate forms of USN, reflecting impaired processing of spatial representations with distinct coordinates (as proposed in Caramazza & Hillis, 1990a; Buxbaum & Coslett, 1994) or a single form of USN that necessarily affects processing of spatial representations across all coordinate frames (as proposed by Behrmann & Moscovitch, 1994; Farah, Brunn, Wong, Wallace, & Carpenter, 1990). The strongest evidence for the independence of different forms of USN would be the existence of patients who show USN only at one level of representation and other patients who show USN only at a different level of representation.

Much of the discussion about coordinate frames of representation in visual object recognition has taken place in the context of a model that Marr (1982; Marr & Nishihara, 1978) developed on the basis of considerations about the computational demands of object recognition (see also Feldman, 1985; Hinton, 1981). Marr hypothesized that object identification requires the computation of at least three levels of representation that are increasingly abstract—i.e., each representational level retains less information about the physical properties of the stimulus than does the previous level. The first level of representation is a “primal sketch” in which the features correspond to the “bars” and “blobs” or discontinuities in light intensities in the stimulus, and its coordinates are those of the viewer’s visual field. The next level of representation is a “2.5-D sketch” in which the features of the stimulus are represented as surfaces oriented with respect to the viewer. The third level of representation is a “3-D model” of the object in which the coordinate frame is defined by the axes of the object itself, so that the orientation of the physical stimulus (e.g., backward or upside down) and its location with respect to the viewer (e.g., to the right or to the left) are no longer represented. Marr describes the primal sketch and the 2.5-D sketch as

“viewer-centered” and describes the 3-D sketch as “object-centered.” We adopt a similar framework, but propose that a stimulus-centered representation is computed from the viewer-centered 2.5-D sketch, prior to the computation of an object-centered representation (see Hillis & Caramazza, 1995a and Rapp & Caramazza, 1991 for empirical evidence).

We use the term “viewer-centered” to refer to any representation in which the midline or midplane of the representation corresponds to the midline or midplane of the viewer’s visual field, head, or body. In most experiments reported here (and elsewhere), these potential reference frames—visual field-centered (retinotopic), head-centered, and body-centered—are confounded. That is, in most tasks subjects are responding to stimuli directly in front of them, such that retinotopic, head-centered, and body-centered coordinates or axes are in alignment. Therefore, one cannot be more specific about the coordinates that influence USN in this typical testing situation. In such a situation, responses that seem to be sensitive to the location of the stimulus relative to the visual field cannot be distinguished from responses that are sensitive to the location of the stimulus with respect to the head or body midplane. Of course, retinotopic, head-centered, and body-centered reference frames can be dissociated by pulling these frames out of alignment (see Bisiach et al., 1985; Calvanio et al., 1987; Ladavas, 1987). For example, one can ask subjects to turn their heads to look at stimuli, so that the body and head of each subject are out of alignment. We will report results from an experiment in which this is done. But in tasks in which we have no specific evidence for one of these reference frames, we use the terms “viewer-centered” to encompass these three aligned frames: retinal-, head-, and body-centered frames of reference.

We use the term “stimulus-centered” representation to refer to a mental representation of a stimulus in which the right and left are defined by the viewer’s right and left, but in which the absolute location of the stimulus relative to the viewer is unimportant. That is, the  $x$ ,  $y$ , and  $z$  axes of the stimulus are parallel to those of the viewer, but do not necessarily coincide. Thus, the stimulus “inherits” right and left from the viewer, but the parts and extent of the stimulus are defined by the midplane, or  $y$  axis, of the stimulus and not the  $y$  axis of the viewer. To illustrate, if the word DOG is presented to the viewer’s right side, the O is the midline of the stimulus but does not correspond to the midline of the viewer. Nevertheless, the D is toward the viewer’s left, as well as toward the left of the stimulus, relative to the O. If the word DOG is written in mirror reversed print, however, the D will be toward the right of the stimulus and the right of the viewer, relative to the O.

Our use of the term object-centered is comparable to Marr’s use of this term. It refers to the coordinate frame defined by the canonical or inherent properties of an object, irrespective of the orientation or location of the object relative to the viewer. The  $x$ ,  $y$ , and  $z$  axes of the object may or may not be

parallel to those of the viewer. At this level of representation of the word DOG, D always has the same relative position (to the "left" of the O), irrespective of whether it is presented in standard print, mirror-reversed print, or spelled aloud. In summary, we propose that object recognition involves computing, in turn, a viewer-centered (retinotopic, head-centered, and/or body-centered) representation, a stimulus-centered representation, and an object-centered representation.

In order to distinguish among the coordinate frames that might be affected by USN two spatial relationships must be manipulated: the orientation of the object and the location of the object with respect to the viewer. Manipulating the orientation of the object with respect to the viewer allows the distinction between object-centered versus stimulus/viewer-centered USN (Behrmann & Moscovitch, 1994; Behrmann & Tipper, 1994; Caramazza & Hillis, 1990a, b; Driver & Halligan, 1991; Hillis & Caramazza, 1990, 1995a, b; Tipper & Behrmann, 1996; Young, Hellaewell, & Welch, 1992). Object-centered USN results in failure to process one side of the "canonical representation" of objects with inherent left and right sides (e.g., words, letters, certain flags, or maps), irrespective of the orientation and location of the object in the visual field. For example, some patients neglect the final letters (or the initial letters, depending on whether the lesion is to the left or the right hemisphere, respectively) of a word even when the final (or initial) letters fall on the ipsilesional side of the patient, as in mirror reversed writing (Baxter & Warrington, 1980; Barbut & Gazzaniga, 1987; Caramazza & Hillis, 1990a, b; Hillis & Caramazza, 1990, 1995a). In contrast, stimulus-centered or viewer-centered USN results in failure to process the left or right side of the physical stimulus, where the left or right are defined by the viewer's left or right, whether or not it is the inherent left or right side of the object. For instance, patients may neglect the initial letters of words in standard print but the final letters of words in mirror reversed print (Hillis & Caramazza, 1991, 1995a; Nichelli, Venneri, Pentore, & Cubelli, 1993) or of words rotated 180 degrees (Riddoch, Humphreys, Cleton, & Fery, 1990).

The second spatial manipulation—varying the location of the object with respect to the viewer (the viewer's visual field or midplane of the head or body)—can decouple stimulus-centered USN from viewer-centered (retino-, head-, or body-centric) USN. Stimulus-centered USN would result in failure to process one side of the viewed stimulus, irrespective of its location in the viewer's visual field or environment. For example, patients have been reported who neglect the left side of words even when these are presented fully in the right visual field (Kinsbourne & Warrington, 1962; Ellis, Flude, & Young, 1987; Ellis, Flude, & Young, 1983; see also papers in Riddoch, 1991 and Arguin & Bub, 1993, for evidence of stimulus-centered USN in nonlexical tasks). In contrast, viewer-centered USN would result in failure to process stimuli that fall on one side of the patient's left visual field, head, or body. Thus, patients might misread words only when they are

presented in the left visual field. This pattern of performance has not, to our knowledge, been previously described in detail. Therefore, the focus of this paper is to report analyses of the performance of patients who show strong effects of the orientation of the stimulus (and thus, no evidence of object-centered USN) *and* significant effects of the absolute location of the object with respect to the viewer (thus, positive evidence of viewer-centered USN rather than stimulus-centered USN). These results provide evidence for the hypothesis that viewer-centered USN exists *and* can occur independently of stimulus-centered and object-centered USN. In one patient, further tests showed that the viewer-centered USN was retinotopic (centered with respect to the residual visual field) rather than head-centered or body-centered.

In this paper we describe three patients with left-sided neglect—CS, AS, and AWR—who show a pattern of performance in reading and nonverbal tasks that is attributable to USN specific to a viewer-centered coordinate frame. Furthermore, for the one patient who was administered tasks that distinguish between retinotopic versus head-centered or body-centered USN, performance clearly indicates retinotopic USN. Two of the three patients (CS and AS) have full visual fields on confrontation, so the results for these patients cannot be attributed to impaired “sensation” on the side contralateral to brain damage. Although the third patient, AWR, has clear homonymous hemianopia, and differs from the other two in her pattern of performance on certain experiments, we argue in the Discussion that her errors are also unlikely to be solely attributable to impaired peripheral visual sensation. In support of this argument, we show that performance on experimental tasks by AWR, AS, and CS contrasts with performance by a control subject with homonymous hemianopia without evidence of USN.

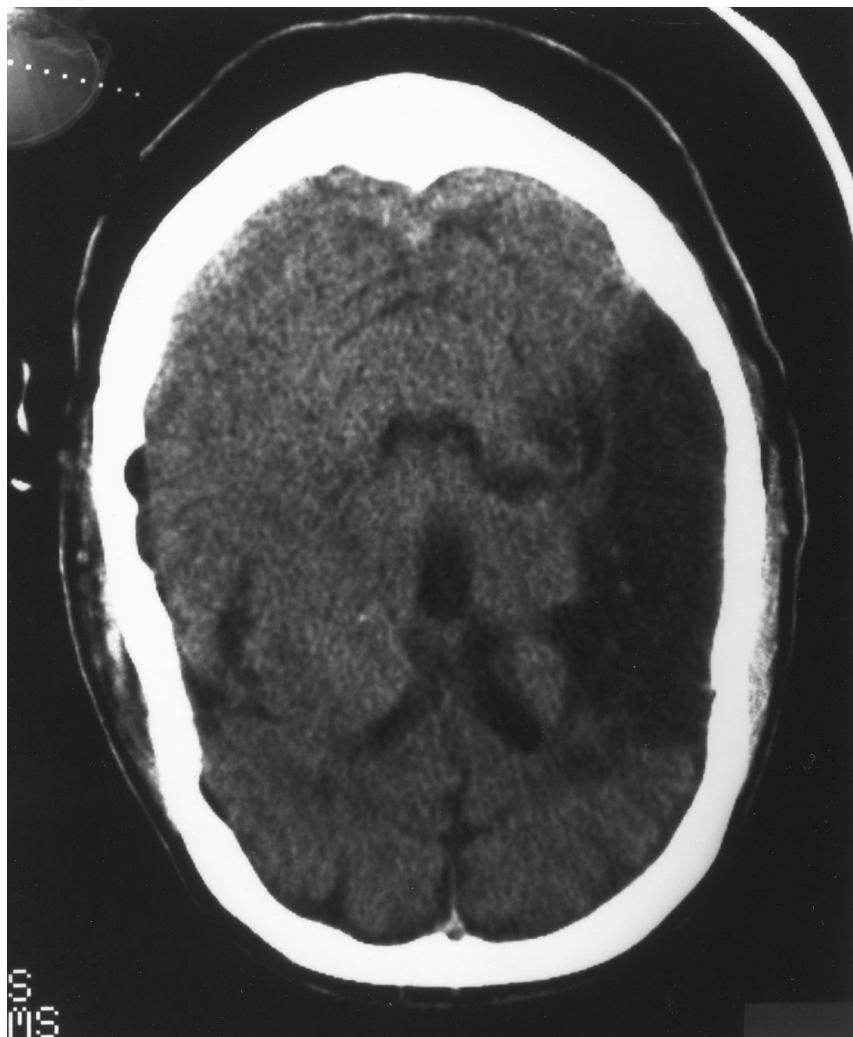
The overall pattern of results provides evidence for the role of an independent viewer-centered (which is, in at least one case, retinotopic) level of representation in word recognition and other visual object processing.

## METHODS

### *Subjects*

Patients were identified from among a large number of patients with USN referred from neurologists, rehabilitation centers, or stroke clubs. CS was tested from 3 to 20 months poststroke. AS was tested at 84–90 months poststroke, and AWR was tested from 74 to 96 months poststroke. All patients showed relatively stable performance over the many (>50) testing sessions.

CS. CS is a 66-year-old, right-handed, retired salesman who graduated from vocational school after completing the eighth grade. Three months prior to the onset of this investigation he awoke with left-sided weakness and slurred speech. A CT scan on admission to the hospital was reportedly normal. A repeat CT scan 48 h after admission showed a large hemorrhagic infarct in the right middle cerebral artery (MCA) distribution, with a 15-mm midline shift, consistent with hemorrhagic conversion of an MCA infarct. The right lateral ventricle was completely effaced, and the pontine cistern was obliterated. Follow-up CT scans showed resolution of the hemorrhage and the cerebral edema (see Fig. 1 for CT scan of CS 20 months



**FIG. 1.** CT scans of CS at 20 months poststroke (at the time of testing).

poststroke). After 2 months of inpatient rehabilitation his hemiparesis improved to mild weakness in his left upper extremity, and he became independent in all activities of daily living except driving. His left neglect, noticeable on all pencil and paper tasks as well as walking and eating, persisted.

Cognitive testing at 3 months poststroke, when he was living at home, revealed normal performance on the Wechsler Memory Scale (1945, 1972) personal and current information, orientation, "logical memory" (passage recall), forward digit span, and associative (word pair) learning. Speech production and auditory comprehension were unimpaired. He had a shallow awareness of his deficits as well as left neglect (described in detail in the experimental section). Neurological examination was otherwise significant for mildly decreased

strength in his left arm. Cranial nerve function was normal. Visual fields were tested by one of the authors (AH), using two methods of confrontation testing: rapid finger movements and finger counting. Using each method, on two occasions each, his visual fields were full. He showed consistent left visual and tactile extinction with double simultaneous stimulation.

**AS.** AS is a 69-year-old, right handed, retired mechanical engineer with a college education. He had sustained a large right middle cerebral artery stroke 7 years before testing. Unfortunately, detailed medical records from the time of his stroke and CT scans are no longer available. At the time of testing he was alert and cooperative with normal auditory-verbal language skills. His scores on the Wechsler Memory Scale were normal on all subtests except visual reproduction. He showed significant left neglect in all spatial tasks, but denied any perceptual, attention, or motor deficits. Visual fields were tested by one of the authors (AH), using two methods of confrontation testing: rapid finger movements and finger counting. Using each method, on two occasions each, his visual fields were full. Cranial nerves were intact with the exception of a mild left central facial palsy. He had complete left hemiplegia and consistent left tactile and visual extinction. Because of his marked USN and denial of deficits he remained dependent on others for help in activities of daily living.

**AWR.** AWR is a 61-year-old, right-handed, high school graduate who sustained a hemorrhagic stroke, due to rupture of a right middle cerebral artery aneurysm 6 years before testing. She had hydrocephalus requiring a ventriculoperitoneal shunt and a seizure disorder following the stroke. A recent head CT scan (9 years post-intracerebral hemorrhage) is shown in Fig. 2. Seizures have been well controlled on carbamazepine. She has persisting left spastic hemiparesis, which is more severe in the upper than in the lower extremity. She has flexion contractures in the left hand and foot. Recent Humphrey visual field threshold testing showed a sharp left homonymous hemianopia without "macular sparing." Visual evoked response testing confirmed a lack of response to visual stimulation in the left visual hemifield. She is aware of her field cut and her motor deficits. Her speech and comprehension are normal, and her scores on the Wechsler Memory Scale at the time of this investigation were normal on all subtests except visual reproduction, in which she made errors on the left side in drawing figures from memory. She is independent in daily activities other than driving.

**SWR (hemianopic control subject).** SWR is a 64-year-old, right-handed female high school graduate. Two months prior to testing she sustained a small left occipital infarct 1 day after surgery for removal of a benign pelvic mass. A CT scan showed a small area of low density in the medial left occipital lobe, consistent with an acute infarct. Her neurological examination was normal, except for right homonymous hemianopia and slightly reduced vibratory sensation in a stocking/glove distribution due to diabetic peripheral neuropathy. Uncorrected vision poststroke was 20/50 in the right eye, 20/70 in the left eye. Just prior to our investigation, SWR had perimetric visual field testing, which documented right homonymous hemianopia without "macular sparing."

## Procedures

The patients were each tested one to three times per week either in their own homes or in an outpatient rehabilitation center for 1- to 2-h sessions. Some of the tasks were not administered to all of the patients simply because the tests (or particular stimulus lists) were developed after one or more of the patients was no longer available for testing (AS moved out of state and CS died of a myocardial infarction). Procedures pertaining to specific tasks are detailed below.

**Reading.** The stimuli for reading standard print and mirror-reversed print and for recognition of aural spelling consisted of lists from the Johns Hopkins University Dyslexia Battery (Goodman & Caramazza, 1986a). This battery includes 325 words and 84 nonwords. Stimuli for reading were printed in block letters in large print. There were no time constraints on re-



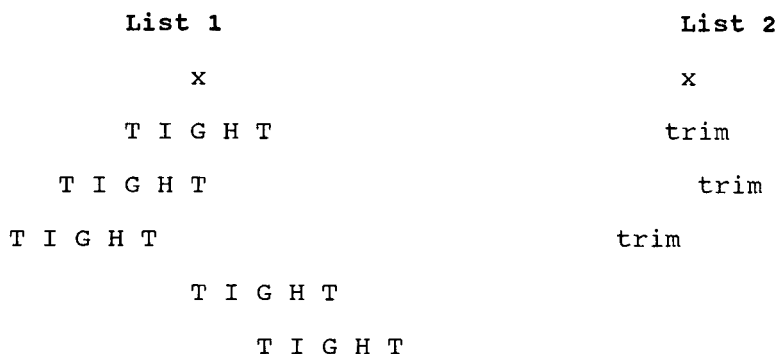


FIG. 2. CT scans of AWR 9 years post intracerebral hemorrhage.

sponding. The lists were presented in the various formats on separate sessions, so that the same word was never presented more than once in a given session. The stimuli for reading vertical print consisted of 42 four-letter words. Equal numbers of words came from the following sets: (1) words that share all but the first letter with other English words (e.g., *west* shares all but the initial letter with *best* and *lest*); (2) words that share all but the last letter with other English words (e.g., *slim* shares all but the final letters with *slip* and *slit*), and (3) words that share the first three letters with at least 1 other real word not on the list *and* share the final three letters with at least 1 other word not on the list (e.g., *weed* shares final letters with *seed* and initial letters with *weep*). For vertical print, letters of the word were written with the first letter at the top and the final letter at the bottom.

To identify the effect of the spatial extent of the physical stimulus, a list of 82 words (five to eight letters in length) was presented in three formats on 3 different days: once with





**FIG. 3.** Locations of stimulus presentation in tachistoscopic reading tasks with respect to the fixation point (an X or an O).

no spaces between letters (e.g., *cough*), once with two spaces between each pair of letters (*c o u g h*), and once with three spaces between each pair of letters (*c o u g h*). The words that served as stimuli share all but the first letter with at least 1 other English word. For example, *wicked* shares final letters with *licked*, *picked*, *ticked*, etc.) and *tumble* shares final letters with *humble*, *mumble*, *rumble*, *fumble*, etc.

For the tachistoscopic reading tasks, two lists of 75 words each were presented for 200 ms for oral reading on a computer screen. The first list (administered to CS, AS, and AWR) was composed of five-letter words, of which one half (38) share the final four letters with at least one other word not on the list and one half (37) share the initial four letters with at least one other word. The mean frequencies of the two types of words were 49 and 45, respectively (Kucera & Francis, 1967). The words were presented in one of five different positions with respect to the fixation point, so that 5 words of each type (selected randomly from the list) were presented at each position in each session. The patient was required to name the fixation point (X or O), which then disappeared before presentation of the word (see Fig. 3). There was one space between each letter in the word to exaggerate the differences in the position of presentation on the screen (e.g., WOUND). Hence, the initial letter of words in position 1 was 10 spaces to the left of the fixation point. The task was repeated six times, for a total of 60 words presented in each position.

The second list (administered to AWR only) was composed of 75 four-letter words, each of which shares the first three letters with at least 1 other real word not on the list *and* shares the final three letters with at least 1 other word not on the list (e.g., *hang* shares final letters with *sang* and initial letters with *hand*). The list was presented for two sets of three sessions; in a given session  $\frac{1}{3}$  of the words appeared to the left of the fixation point,  $\frac{1}{3}$  appeared to the right of the fixation, and  $\frac{1}{3}$  appeared in the center (in place of the fixation; see Fig. 3). The position of presentation was changed each session, so that each of the words appeared in all three positions in each of the two sets.

**Line bisection.** Each patient was presented with five horizontal lines of each of the following lengths: 10, 15, 20, and 25 cm, for a total of 20 trials. Each line was centered on an  $8\frac{1}{2} \times 11$  in. sheet of paper. Lines of the various lengths were presented randomly and were placed directly in front of the patient on a flat surface. The subject was instructed to mark the center of the line. This procedure was repeated, with the additional instruction to mark each end of the line with an "X" before marking the midline. Bisection of identical sets of vertical lines, oriented parallel to the subject's primary vertical axis was also tested, using the same stimuli presented on a wall in front of the subject.

*Letter detection.* Two tasks of letter detection were used. Methods used in each task are described separately.

*Task 1* (administered to CS, AWR, and SWR). Stimuli consisted of displays of five horizontally arrayed letters. Half of the displays were made up of five O's, while the other half had four O's and 1 X. The X appeared equally often in each of the five positions. All letters were capitals, and there was one space between the letters. The displays were presented randomly at one of five different display locations across the same horizontal row, centered around a central fixation point: two at positions to the left of fixation, two to the right, and one straddling fixation. Stimuli subtended an angle of  $4^\circ$ , with a maximum eccentricity of  $7^\circ$ . A total of 1000 stimuli were presented to each patient. On each trial a fixation point ":" was displayed for 500 ms followed by a 150-ms pause. Stimuli were displayed for 200 ms, and then subjects were asked to press a key as quickly as possible if an X was present.

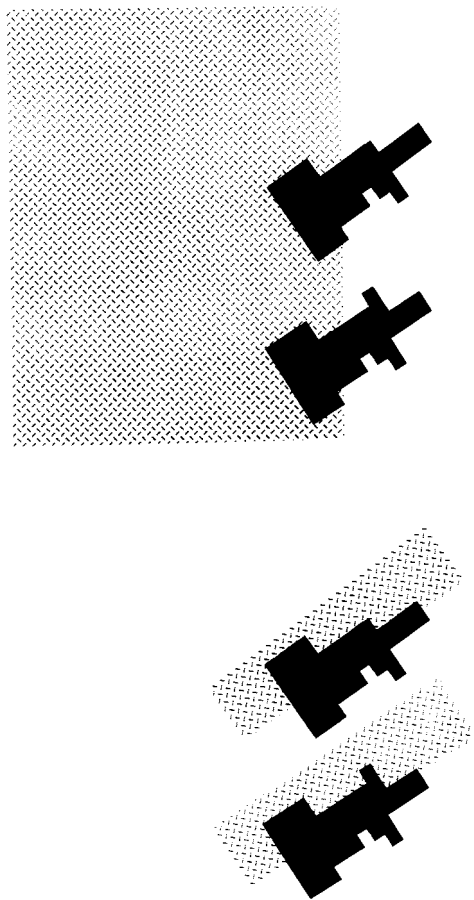
*Task 2* (administered to CS and AS). Stimuli consisted of displays of three- and seven-letter strings with one space between the letters. Uppercase K, X, Z, N, or Y served as target letters. The distractors were D, J, G, R, B, and P. A target was present among distractors on half of the trials. Half of the stimuli contained seven letters and half three letters. The three letter stimuli were presented in five locations: two to the left of fixation, two to the right, and one straddling fixation; the seven-letter strings covered all of these seven locations. Stimuli subtended an angle of approximately  $2^\circ$ , with a maximum eccentricity of approximately  $2.5^\circ$ . On each trial the target letter was presented at the central fixation position for 150 ms. The subject was instructed to look for this letter in the subsequent stimulus display. Upon offset of the target letter, a stimulus was displayed for 250 ms. The subject was asked to press a key as quickly as possible if the target letter was in the string. A total of 1000 stimuli (500 three letter strings, 500 seven-letter strings) were presented to each patient.

*Detecting differences between abstract shapes.* This task was designed by Driver and Halligan (1991). The stimuli and procedures are described in detail in that paper. Briefly, the non-sense shapes that serve as stimuli are vertically elongated and bottom heavy in order to give the shape an unequivocal principal axis. Each shape is 10 cm tall, with a base of 5 cm width, created by blacking squares in a  $10 \times 5$  grid. There are 8 shapes plus their mirror images, for a total of 16. Two shapes, 1 above the other, are printed on  $8.5 \times 11$  in. white paper. Each shape was presented once with an identical shape and once with a shape that differed only on the left or on the right (by one or two squares of the grid; see Fig. 4). Each of the 32 pairs was presented three times: once printed vertically on the page, once rotated  $45^\circ$  clockwise, and once rotated  $45^\circ$  counterclockwise on the page. The patient was instructed to state whether or not the two shapes were identical. There were no time constraints. Head movements were discouraged, but there was no effort to control eye movements. The task was administered twice to each patient.

*Blindfolded searching for marbles.* For this task of motor exploration of space, a  $1 \times 3$  ft array made of foam egg crate was placed directly in front of the patient. He or she was allowed to examine it prior to being blindfolded. Then, 86 marbles were placed in the indentations of the egg crate in a symmetrical pattern across the array. The patient was instructed to find and pick up all the marbles. Each marble was taken from the patient's hand after it was picked up. There were no time constraints; the task was discontinued when the subject reported having found all the marbles.

## RESULTS

Below we report the performance of three patients with hypothesized viewer-centered USN on a number of tasks that were designed to disentangle the frames of reference at which USN might occur. Alongside these patients' performance we report contrasting published results on the same tasks by



**FIG. 4.** The same stimulus from Driver and Halligan (1991), as perceived in the presence of left USN at (a) a viewer-centered (e.g., retinocentric) level of representation and (b) an object-centered level of representation.

patients whose performance has been accounted for by proposing object-centered or stimulus-centered neglect.

#### *Tasks That Distinguish USN from Homonymous Hemianopia*

In reading standard (left to right) print, CS, AS, and AWR all made errors predominantly on the initial letters of the word in standard print, such as *ideal* → “steal,” *gut* → “out,” and *picked* → “backed” (Table 1 and Appendix). In contrast, SWR, our control patient with homonymous hemianopia without USN, made almost no errors (fewer than 1% of words). The few errors she made in reading 494 words from the Johns Hopkins Dyslexia

TABLE 1  
Percent Spatially Specific Errors (of Total Errors) in Reading Standard Print by Patients  
with Proposed USN at Different Levels of Representation

	Percentage of errors just on the initial letters	Percentage of errors just on the final letters
Viewer-centered USN (all RHD) <sup>a</sup>		
CS	97	0
AS	93	0
AWR	100	0
Homonymous hemianopia without USN		
SWR (RHD)	10	10
Results from patients in the literature <sup>b</sup>		
Stimulus-centered USN		
RW (RHD)	79	2
GG (RHD)	93	<8
BPN (RHD)	97	0
Object-centered USN		
NG (LHD)	0	96
HB (LHD)	0	89
ML (RHD)	90	0
JL (RHD)	"Most"	

<sup>a</sup> LHD, left hemisphere damage; RHD, right hemisphere damage.

<sup>b</sup> NG was reported in Hillis and Caramazza (1990) and Caramazza and Hillis (1990). HB and ML are described in Hillis and Caramazza (1995a). JL was reported by Barbut and Gazzaniga (1987), who did not report precise percentage of errors restricted to the left. GG was reported by Nichelli et al. (1993); RW was reported by Hillis and Caramazza (1991). Details of BPN are described in Hillis and Caramazza (1995b).

Battery (Goodman & Caramazza, 1986a) were not restricted to either end of the word or pseudoword [e.g., *deny* → "denny"; *quay* → (kweI), rhyming with bay; *kittul* → "kit-full"].

### *Tasks That Distinguish Viewer-Centered or Stimulus-Centered USN from Object-Centered USN*

*Manipulation of orientation and modality.* Reading vertical print and mirror-reversed print and recognition of aurally spelled words manipulated the variable of orientation (or modality of presentation). Left viewer-centered or stimulus-centered USN should result in few errors on vertically printed words or words spelled aloud (since these stimuli do not have a left or right side) and errors on the final letters of words in mirror-reversed print (since these letters would fall on the left side of the viewer and the stimulus). In contrast, left object-centered USN should result in errors on the initial letters, at a similar rate in all tasks (since an object-centered representation would be the same in all three tasks).

In reading vertical print, patients in this study made either no errors

TABLE 2  
Performance on Vertical Reading by Patients with Proposed  
Damage at Various Levels of Representation

Viewer-centered level			
Predicted:	Standard lower than vertical		No spatial specificity in error production
Data:	% Correct standard	% Correct vertical	(% of errors (of total errors) just on contralesional side of the canonical word)
CS	83	96	0%
AS	67	98	0%
AWR	91	100	0%

Results from patients in the literature			
Stimulus-centered level			
Predicted:	Standard lower than vertical		No spatial specificity in error production
Data:	% Correct standard	% Correct vertical	(% of errors (of total errors) just on contralesional side of the canonical word)
BPN	47	96	0
RW	72	90	33

Object-centered level			
Predicted:	Standard equal to vertical		Most errors just on contralesional side
Data:	% Correct standard	% Correct vertical	(% of errors (of total errors) just on contralesional side of the canonical word)
NG	72	75	97

(AWR) or only a few errors (CS and AS; see Table 2). The few errors produced by CS and AS were distributed throughout the word (CS: *hose* → “horse”; AS: *give* → “g-i-w-e..goeey”). The hemianopic control, SWR, also made no errors. Similarly, in recognition of aurally spelled words, CS, AS, and AWR made fewer than 1% errors, and the occasional errors that were produced involved letters in the center of the word. Likewise, the few errors made by the hemianopic control subject involved letters in the middle of the word (e.g., *p-a-r-t-i-a-l* → “parallel”). In reading mirror-reversed print, CS, AS, and AWR made errors on the final letters of the words at approximately the same rate as they made errors on the initial letters of words in standard reading. For instance, CS made, respectively, 30 and 27% errors

TABLE 3  
Rate of Errors as a Function of Spacing between Letters (# in correct/total  $\times$  100)

Proposed level of USN	No spaces	2 spaces	3 spaces	0 vs. 3 spaces $\chi^2$ value
Viewer-centered				
CS	0	19	28	26.7 ( $p \ll .0001$ )
AS	22	30	41	7.17 ( $p < .01$ )
				Fisher exact: $p < .01$
AWR	2	8	10	3.78 ( $p = .05$ )
				Fisher exact: NS
Hemianopia without USN				
SWR	0	0	0	
Results from patients in the literature				
Stimulus-centered USN				
BPN	53	65	95	11.3 ( $p < .001$ )
RW	6	11	22	8.53 ( $p < .01$ )
Object-centered USN				
NG	24	26	23	0.03 (NS)

on the two tasks using the same stimuli, but his errors were on the initial letters in standard reading, and they were on the final letters in mirror-reversed reading (e.g., *lick*  $\rightarrow$  "licked"; see Appendix). SWR, the hemianopic control subject, made no errors in mirror-reversed reading.

*Manipulation of the spatial extent of the stimulus.* In this experiment, each stimulus word was printed with 0, 2, or 3 spaces between the letters (e.g., c o m m o n), so that the initial letters would be further to the absolute left of the viewer (further to the left side of the visual field/head/body), and further to the left of the center of the stimulus, but unchanged with respect to the distance from the center of the abstract, canonical representation of the word.

The USN patients in this study showed a significant effect of spacing on reading. Errors on the initial letters increased as a function of the number of spaces between letters, as predicted by the proposal of viewer- or stimulus-centered USN (Table 3). The hemianopic control subject made no errors on these words, irrespective of the number of spaces between letters.

### *Tasks That Distinguish Viewer-Centered from Stimulus-Centered USN*

The data we have reported to this point are consistent with the proposal of a deficit in processing the contralesional side of a viewer-centered (retinal-, head-, or body-centered) representation *and/or* a stimulus-centered representation. On the basis of this evidence we are able to rule out the presence of object-centered USN in our patients. We now present data on tasks that further distinguish viewer-centered USN level from stimulus-centered USN. These tasks manipulate the location of the stimulus with respect to the



TABLE 4

Rate of Errors in Reading as a Function of Position on Page (# incorrect/total  $\times$  100)

Proposed level of USN	Position of word on the page				
	Far left	Left	Center	Right	Far right
Viewer-centered					
CS	25	17	8	0	0
AS	100	42	25	8	0
AWR	17	8	0	8	8
Results from patients in the literature					
Stimulus-centered (RW)	17	18	29	0	17
Object-centered (NG)	28	22	26	28	25

viewer. In the presence of viewer-centered USN, reading performance should vary as a function of the location of the word with respect to the viewer: words on the left side of the viewer's visual field, head, or body should be read less accurately than words on the right side. Words presented on the right side of the viewer should be read normally. But in the presence of stimulus-centered or object-centered USN, the location of the word with respect to the viewer should not affect reading accuracy, since the relative left side of the stimulus word and of the canonical "object" are identical across all locations.

*The effect of the location of the word on the page.* In reading words in one of five columns across the page, the patients in this study show more errors on the left side of the page (Table 4). The difference in error rates in the two left columns compared to the two right columns in this task was significant for AS (71% vs. 4%;  $\chi^2(df, 1) = 22.8$ ;  $p \ll .0001$ ) and CS (21% vs. 0%;  $\chi^2(df, 1) = 5.58$ ;  $p < .02$ ; Fisher Exact:  $p < .05$ ). AWR showed a nonsignificant trend in the expected direction (13% vs. 8%, for left vs. right columns). SWR (the hemianopic control subject) made no errors on any of these words.

*Tachistoscopic reading.* In reading words presented for 200 ms. CS, AS, and AWR made more errors on words presented to the left of fixation (Table 5). The higher rate of left-sided (initial letter) errors for words presented to the left than for words presented to the right was significant for CS (33% vs. 7%;  $\chi^2(df, 1) = 10.04$ ;  $p < .01$ ) and AWR (60% vs. 3%;  $\chi^2(df, 1) = 22.6$ ,  $p \ll .0001$ ). AS was not tested on tachistoscopic reading. All patients who were tested in the tachistoscopic task made many errors at all locations in the visual field, presumably because of the brief presentation time and other characteristics of the display. Still, nearly all their errors were either left-sided errors or failures to respond.<sup>1</sup> Interestingly, the further to the right

<sup>1</sup> In view of her homonymous hemianopia (confirmed by visual evoked response testing) in addition to USN, it is somewhat surprising that AWR was able to read any words on the

TABLE 5  
Total Error Rate in Reading as a Function of Position in Visual Field

Proposed level of USN	Position of word in the visual field		
	Left	Center	Right
Viewer-centered			
CS	53 (33)	60 (53)	17 (7)
AWR	80 (60)	80 (53)	53 (3)
Contrasting results from patients in the literature			
Object-centered (NG)	20 (17)	23 (23)	21 (17)

*Note.* Rate of errors restricted to the contralesional side of the stimuli given in parentheses.

the word was presented, the more letters were read correctly. To illustrate from AWR's performance, when presented on the right, the word *found* was read as "hound" (preserving 4 letters); when presented in the center, the word *mount* was read as "unt" (preserving 3 letters); and when presented on the left, the word *count* was read as "t" (preserving 1 letter). In contrast, errors by a patient with object-centered USN were essentially identical at all positions (see Table 6).

SWR (the hemianopic control subject) also made many errors in reading words presented tachistoscopically, and showed a significant effect of visual field (64% accuracy in the left field, 24% in the right field;  $\chi^2$  (*df*, 1) = 8.12;  $p < .005$ ; Fisher's Exact:  $p < .01$ ). The majority of her errors at all locations of the visual field involved correct identification of a few letters (e.g., LOVES → "l-o-u"; MERRY → "m-e-r"). Additionally, when presented with words completely on the right, in her blind hemifield, she often failed to respond at all or guessed based on the first letter (e.g., COUGH → "crew"). Her occasional correct responses in the right (blind) hemifield, as well as her errors in the intact left hemifield, probably resulted from failure to maintain fixation. The examiner (LB) saw her shift fixation to the right on many trials. Her impaired reading on this task contrasts markedly to her almost perfect performance on untimed reading tasks.

left visual hemifield. One possible explanation is that she did not maintain fixation, but made eye movements to the left on each trial (after reading the letter at the fixation point) during the presentation of the stimulus. This hypothesis is consistent with the fact that the examiner (LB) saw the patient move her eyes to the left with each trial. This hypothesis would also account for her rather poor performance in reading words presented in her right visual field (53% errors compared to less than 10% errors in untimed reading). These results are similar to those obtained from SWR, the hemianopic control subject who also failed to maintain fixation. We were unable to omit trials in which the subjects made eye movements, since both patients made eye movements to the hemianopic side after fixation in nearly every trial (despite instructions to maintain fixation). Nevertheless, even with consistent eye movements to one side, the words presented on the left remained relatively in the left side of her residual visual field, and words presented to the right remained toward the right side of her visual field.

TABLE 6  
Examples of Errors in Tachistoscopic Reading without Masking

Left position	Center position	Right position
Viewer-centered		
CS		
brown → down	yeast → feast	clove → glove
count → quit	bough → rough	round → mound
never → lower	never → fever	ditch → butch
AWR		
later → _er	mount → _unt	found → hound
beast → _st	bough → _ugh	mail → tail
count → _t	round → _ound	moot → root
frown → _wn	yeast → east	
mouse → house	never → fever	
hitch → witch	tight → light	
Contrasting results from patients in the literature		
Object-centered		
NG		
thin → thing	thin → think	thin → thin
plan → platt	plan → plane	plan → plane
rain → ram	rain → +	rain → ram
wind → will	wind → wisp	wind → win
hard → +	hard → harsh	hard → +

### *Tasks That Distinguish among Viewer-Centered Frames of Reference*

The data presented so far are consistent with the proposal that CS, AS, and AWR have USN at the level of the viewer-centered level of representation. The data indicate that their USN concerns a level of representation in which the center corresponds to the midline of the residual visual field, the head *or* the body. That is, in all of the above experiments, stimuli that were presented further to the left (or right) of the visual field were also presented further to the left (or right) of the midline of the patient's head and the midline of the patient's body. The following experiments carried out with AWR decoupled these possible frames of reference. Regrettably, the experiments required to disambiguate retinotopic versus body- or head-centered coordinate frames were not carried out for CS or AS, since they were no longer available for testing.

When AWR was turned to the left but the head and eyes remain facing forward, so that stimuli were presented fully on the right side of the body (relative to its sagittal midplane), AWR continued to make errors on the left side of her residual visual field/head. When her body was turned to the right, with eyes and head facing forward, so that all the stimuli fell on the left side of her body, AWR showed no hint of more left-sided errors compared to when the word was presented on the right side of her body (Table 7). If anything, she made more errors when words were on the right side of her

TABLE 7

AWR’s Errors on the Initial Letters of Words (on the Relative Left of Her Visual Field) as a Function of the Location of the Stimulus with Respect to the Head and Body Midline

Set	Location of stimulus	Rate of left-sided errors (%)
1	Midline of head and body (head, body, and eyes straight)	3
	Midline of head, left of body (body turned to the right; head and eyes straight)	4
	Left of head, left of body (body and head turned to the right; eyes straight)	3
2	Midline of head and body (head, body, and eyes straight)	9
	Midline of head, right of body (body turned to the left; head and eyes straight)	14
	Right of head, right of body (body and head turned to the left; eyes straight)	14

body. But  $\chi^2$  analysis of the data showed no significant differences between locations of presentation in the rate of left-sided errors. That is, her reading was not significantly influenced by turning her body to the left or the right.

To decouple retinotopic USN (centered with respect to the residual visual field) from head-centered USN, stimuli were presented in such a way that the head and eyes are out of line with each other. Therefore, AWR was tested with her head turned to the left, while her eyes were directed to the stimulus. As shown in Table 7, AWR’s reading was unaffected by turning her head to the right or the left.  $\chi^2$  analysis of the data showed no significant differences between locations—the left versus right side of the head—in the rate of left sided errors. When words were on the right side of her head and the right side of her body she continued to make errors only on the left side (initial letters) of the words. These results are consistent with the hypothesis that AWR’s errors occur on the left side of her residual visual field rather than the left side of her head or body. Of course, since she has a blind left hemifield, we assume that she fixates words so that the entire word falls into her residual visual field, but that she continues to show USN in processing the *relative* left side of her remaining visual field.

*Comment on Reading Tasks*

The errors in reading words in standard print by CS, AS, and AWR were similar to the reading errors attributed to object-centered neglect or stimulus-centered neglect in previous reports. Nevertheless, striking differences in the parameters that affected reading in nonstandard formats and performance on other tasks using the same words indicate a different source of errors in these

patients than in the previously reported patients. The performance of these patients diverged from performance ascribed to object-centered USN in the following ways:

(1) Recognizing aurally spelled words and reading vertical words were both more accurate than reading horizontal words, and only horizontal words elicited errors specific to the side of the word contralateral to brain damage.

(2) Errors in reading mirror-reversed words occurred on the contralesional side of the stimulus/visual field, rather than on the contralesional side of the word (in its canonical, left → right orientation).

(3) Reading was influenced by the spatial extent of the visual stimulus (e.g., the number of spaces between letters).

Together, results 1–3 provide evidence that the deficit concerns one side of the viewer's visual field, or midplane of the body or head, or one side of the visual stimulus (or some combination of these frames of reference). These remaining possibilities were distinguished by data from additional tasks in which performance of the patients in this study differed from performance attributable to stimulus-centered USN. Performance of CS, AS, and AWR diverged from performance ascribed to stimulus-centered USN by Hillis and Caramazza (1991, 1995b; see also Kinsbourne & Warrington, 1962; Ellis et al., 1987; Behrmann, Moscovitch, Black, & Mozer, 1990), in the following ways:

(1) Reading accuracy was influenced by the side of the page on which the word appeared (at least for CS and AS). All three patients made more errors on words printed on the contralesional side of the paper.

(2) Accuracy in reading words presented for brief durations (200 ms) was influenced by its position on the screen and thus its position with respect to the viewer's visual field, head, and body. The patients made more errors on words presented to contralesional (left) locations.

These results indicate that the USN of these patients concerned one side of the visual field or midplane of the head or body. These alternative explanations were distinguished, at least in AWR, by presenting words in the line of sight (centered with respect to the retina), while the head and body were each independently rotated out of line with the eyes. Contrary to predictions of left USN at a level of representation defined in relation to the center of the body, AWR's performance did not improve when words were presented fully on the right side of her body (where the initial letters were still in the left visual field). And, contrary to the predictions derived from the proposal of left USN defined by coordinates relative to the midline of her head, her performance did not improve when stimuli were presented fully on the right side of her head. Her performance also did not deteriorate when stimuli were presented fully on the left side of her body or head.

Thus, the results from AWR's performance on lexical tasks converge in support of the hypothesis that her "neglect dyslexic" errors arise as a consequence of a disruption in processing a level of representation with coordi-

nates defined by the visual field. The generally comparable patterns of performance on lexical tasks carried out with CS and AS might also be accounted for by this proposal, although their USN might have affected a level of representation with coordinates corresponding to those of the head or the body. These conclusions are consistent with our working model of word recognition which specifies at least three levels of representation, including one or more viewer-centered levels (including at least one retinotopic level), a stimulus-centered level, and an object-centered level. Together with reports in the literature of object- and stimulus-centered USN, the present results also provide support for the proposal that USN can affect any one of these levels individually.

### *Nonlexical Tasks*

We have argued that "neglect dyslexic" errors result from a disruption in processing information on the side contralateral to brain damage in one or another of several spatial representations computed in the course of object/word recognition. Word stimuli have provided a convenient type of stimulus for distinguishing among the hypothesized levels of representation. However, in our view, USN is not a material-specific deficit, and consequently the patients in this study should also make errors in processing nonlexical visual stimuli on the absolute left side of the viewer (see Hillis & Caramazza, 1995b, for alternative accounts of cases reported to show material-specific neglect). In contrast, patients with object-centered and stimulus-centered USN should make errors on the left sides of nonlexical stimuli, regardless of the side of the viewer on which the stimulus is presented. These predictions were tested in the following experiments.

*Letter detection as a function of position in the letter string and visual field.* The accuracy of AS, CS, and AWR in identifying the presence of a target letter, in a string of letters presented briefly at various locations in the visual field, was not a function of the position of the letter in the string. Rather, each patient's accuracy at a given position in the string decreased as a function of the distance to the left ("neglected" side) of the fixation point. When results across locations within each hemifield were collapsed, each patient with left USN showed significantly lower accuracy in identifying letters in the left hemifield than in identifying letters in the right hemifield, as follows: for AS: 43% vs. 68% ( $\chi^2(df, 1) = 26.3, p \ll .0001$ ); for CS: 75% vs. 92% for the two tasks collapsed ( $\chi^2(df, 1) = 61.0, p \ll .0001$ ); and for AWR: 18% vs. 73% ( $\chi^2(df, 1) = 244, p \ll .0001$ ). In contrast, three previously reported patients whose USN was ascribed to a deficit at the level of object-centered representations (NG, RB, and HH), made errors in detecting letters on the contralesional side of a string of letters *irrespective* of where in the visual field the string was briefly presented (Hillis & Caramazza, 1990). That is, the difference between error rates on the left and the



TABLE 8  
Performance on the Driver and Halligan Task with Tilted Objects, Given  
in No. Errors/Total Responses and (%)<sup>a</sup>

Location of the difference with respect to the object	Location of difference with respect to viewer (visual field/head/body)		
	Left of viewer	Right of viewer	Total
Viewer-centered USN			
CS (RHD)			
Left side of object	11/32 (34)	2/32 (6)	13/64 (20)
Right side of object	5/32 (16)	7/32 (22)	12/64 (19)
Total	16/64 (25)	9/64 (14)	
AWR (RHD)			
Left side of object	8/32 (25)	4/32 (13)	12/64 (19)
Right side of object	8/32 (25)	4/32 (13)	12/64 (19)
Total	16/64 (25)	8/64 (13)	
Contrasting results from patients in the literature			
Object-centered USN—NG (LHD)			
Left side of object	1/16 (6)	0/16 (0)	1/32 (3)
Right side of object	9/16 (56)	11/16 (69)	20/32 (63)
Total	10/32 (32)	11/32 (34)	

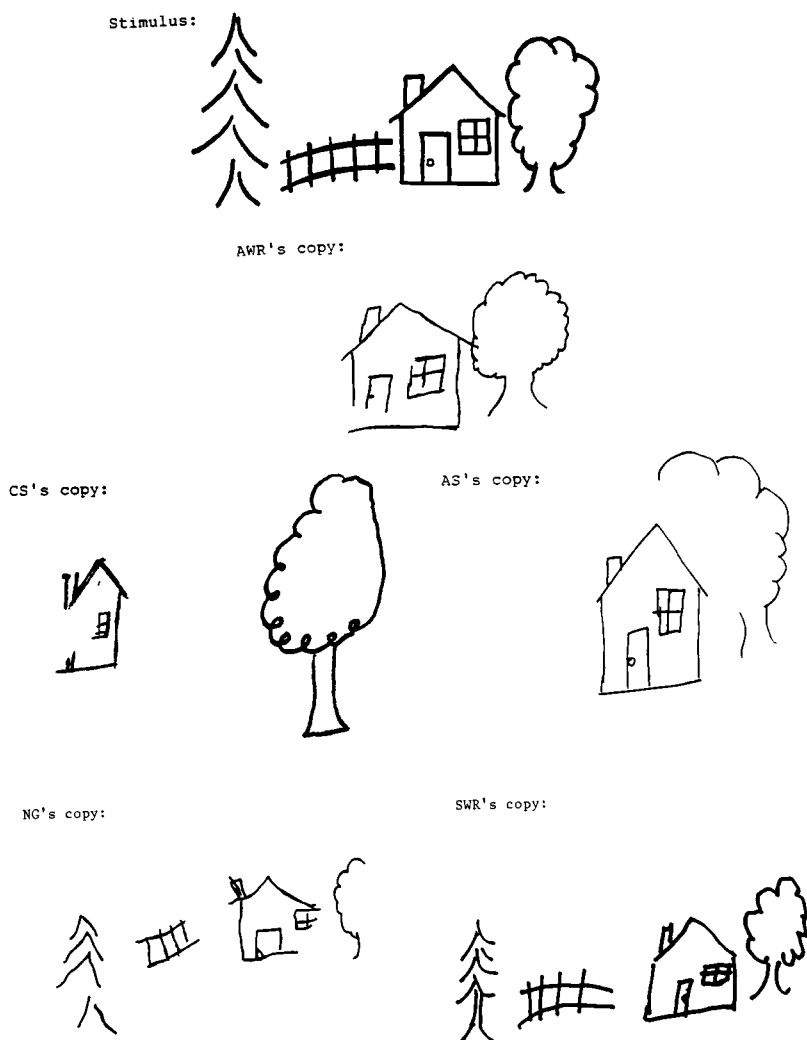
<sup>a</sup> Errors on straight objects are not included in the table, because the side of the object and the side of the paper are confounded for these stimuli.

right sides of the string was highly significant ( $p < .0001$ ), but there was no difference in error rates as a function of position of the string in the visual field, for patients with object-centered USN.

The hemianopic control subject, SWR, showed a similar pattern of performance as the patients with USN in this (AS, CS, and AWR), but involving the opposite side. SWR was significantly more accurate in identifying letters presented briefly on the left (her intact hemifield) than on the right: 82% vs. 27% ( $\chi^2 (df, 1) = 244, p \ll .0001$ ).

*Detecting differences in abstract shapes.* To test the hypothesis that our patients would show similar patterns of USN in processing nonlinguistic, abstract visual shapes, we adopted a task used by Driver and Halligan (1991). In this task, the side of the viewer (retina, head, or body) and the side of the object were disambiguated by rotating vertically elongated abstract shapes, each with respect to its principal axis (Fig. 4).

CS, AS, and AWR each made more errors on the left (contralesional) than the right side of the viewer (visual field/head/body), irrespective of the side of the object on which the difference occurred. The difference between errors on the left versus the right side of the paper was not significant for any of the patients individually (due to the small numbers of trials in each cell), but they each showed the same trend (Table 8). For the 2 patients with postulated viewer-centered USN combined, there was a significant effect of the side of



**FIG. 5.** Direct copies of the "Ogden Scene" by AWR, CS, and AS, in contrast to that of NG (with putative object-centered USN) and SWR (the hemianopic control).

the viewer/environment ( $\chi^2(df, 1) = 5.68, p < .02$ ; Fisher Exact:  $p < .03$ ), but no effect of side of stimulus/object ( $\chi^2(df, 1) = 0.03$ ; NS). In contrast to the results for CS and AWR (AS was not administered this task), Driver and Halligan reported a significant effect of both the side of the viewer/environment *and* the side of object for their patient. Hillis and Caramazza (1995b) reported only an effect of the side of the object in patient NG.

*Copying.* The direct copies of the "Ogden scene" by each of the patients in this study are shown in Fig. 5. In contrast to the drawing by the patient with right USN at the level of object-centered representation, the patients with

USN in this study all omitted the figures on the left side of the viewer (see Gainotti, D'Erme, Monteleone, & Silveri, 1986; Gainotti, Messerli, & Tissot, 1972, for additional cases of these contrasting patterns in copying). The hemianopic control patient produced a normal copy.

*Drawing.* Spontaneous drawings by each patient of a clock, sailboat, a house, and a flower were much more accurate than copying of the same figures. None of the spontaneous drawings showed any clear evidence of spatial neglect.

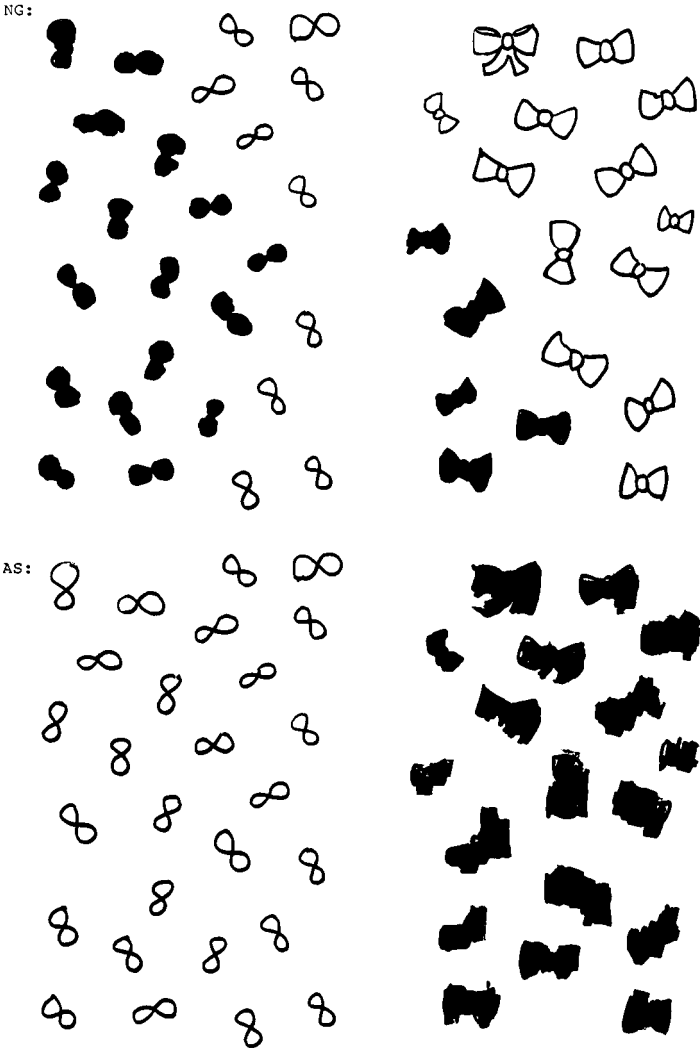
*Line bisection.* In bisecting horizontal lines, CS deviated to the right by a mean of 20% of the line length, irrespective of the length of the line. In bisecting vertical lines, he deviated upward by a mean of 0.9% of line length. Similarly, AS showed a mean deviation to the right of 15.5% in bisecting horizontal lines and a mean downward of 0.9% in bisecting vertical lines. AWR showed a mean deviation to the right of 6.3% in bisecting horizontal lines and a mean deviation upward of 0.8% in bisecting vertical lines. Only AS showed a clear pattern of greater error on longer lines (with respect to both absolute distance and proportion of line), for horizontal lines only. The mean deviation to the right of horizontal lines of various lengths in percent of line "neglected" was as follows: 25 cm: 21%; 20 cm: 19%; 15 cm: 14%; 10 cm: 8.2%. None of the patients showed a significant difference in performance when they were asked to mark the end of each line before bisecting it. AS and CS were also tested with the horizontal lines entirely to the left, or entirely to the right, of the mid-sagittal plane of the body; there was no significant difference in performance when the location of the line was varied. SWR (the control subject) showed a deviation to the right of horizontal lines of 1.6% of line length. She was not tested on vertical lines.

*Line cancellation.* In a variant of the line cancellation task (Albert, 1973), in which items for "cancellation" were presented in separate groups, that might each be attended to as a separate stimulus or object, AS, CS, and AWR omitted all items in the left group. In contrast to these patients with proposed left viewer-centered USN, previously reported patients with object-centered USN made errors on the contralesional side of each "group" (Fig. 6; see also Driver & Halligan, 1991). The hemianopic control subject did not omit any lines or targets in any of the cancellation tasks administered to CS, AS, or AWR.

*Blindfolded searching for marbles.* In this task, each of the patients and the control subject found all 86 of the marbles distributed throughout a 1' × 3' foam egg crate, when they were blindfolded. In contrast, NG and ML (with proposed object-centered neglect) omitted the marbles on the contralesional side of the egg crate.

#### *Comment on Performance in Nonlexical Tasks*

The results we have reported for nonlexical tasks mirror those for lexical tasks. Performance of the patients in this study diverged from performance attributed to object-centered USN in the following ways:



**FIG. 6.** Performance by AS (with proposed viewer-centered USN) contrasted to NG (with proposed object-centered USN) on a cancellation task.

- (1) Errors in line bisection, “cancellation” and copying tasks concerned the contralesional side of the page (visual field/body/head) rather than the contralesional side of each object (or group of items) on the page.
- (2) Failures to detect differences between abstract shapes were a function of the contralesional side of the page (visual field/body/head) and not the contralesional side of the shape (rotated with respect to its vertical axis).

(3) Errors in detecting letters in nonlexical strings were a function of the location of the letter relative to the viewer's visual field/head/body.

(4) There were no errors in drawing of named objects or in searching for marbles when blindfolded.

Facts (1) and (2) support the conclusion that USN of these patients arises at the level of computing a stimulus-centered or viewer-centered (retinal-/head-/body-centered) representation. Fact (3) further "localizes" the deficit to the viewer-centered level. Fact (4) provides evidence that the USN in CS, AS, and AWR involves a representation specific to visual processing, in contrast to USN at an abstract level of representation constructed by the subject to guide exploratory movements and construction (as proposed for NG and others with USN apparently affecting object-centered representations or a "visuospatial scratch pad"; Bisiach & Berti, 1987; DeRenzi, Faglioni, & Scotti, 1970; Hornak, 1992).

For the patients in this study, as well as previously reported patients (including those reported by Barbut & Gazzaniga, 1987; Nichelli et al., 1993), the proposal of a deficit at a specific level of representation can account for both the spatially specific reading errors and the spatially specific errors in nonlexical tasks. This association between performance on lexical and nonlexical tasks provides support for the hypothesis that each of the three levels of representation we have proposed is involved in reading and in nonlexical visual processing.

## DISCUSSION

The three patients in this investigation made errors in processing the left side of visual stimuli (whether words or other visual objects). Detailed analyses of performance on a variety of tasks showed that their errors increased as a function of the distance to the left side of the viewer's visual field, head, and/or body. This pattern of performance in lexical and nonlexical tasks by CS, AS, and AWR is explicable by proposing in each case a unilateral deficit in processing viewer-centered (retinal-, head-, or body-centered) representations of visual stimuli, on the side contralateral to brain damage. These results contrast with two previously reported patterns of performance on the same tasks by other neurologically impaired patients. In one of the contrasting patterns, errors increase as a function of the "distance" from the center of the stimulus on the side contralateral to brain damage, but errors are independent of the position of the stimulus with regard to the viewer's visual field and head/body midplane. This pattern is explicable by proposing impaired processing of stimulus-centered representations (Arguin & Bub, 1993; Ellis et al., 1987, 1993; Hillis & Caramazza, 1991, 1995a; Nichelli et al., 1993). In the other contrasting pattern, errors increase as a function of the distance from the center of the canonical object on the side contralateral to brain damage, irrespective of its orientation or location. This pat-

tern can be accounted for by assuming USN at the level of object-centered representations (Baxter & Warrington, 1983; Barbut & Gazzaniga, 1987; Behrmann & Tipper, 1994; Caramazza & Hillis, 1990a, b; Hillis & Caramazza, 1990, 1995a; Tipper & Behrmann, 1996) or representational space (Bisiach & Vallar, 1988). Together, these three distinct patterns of performance provide evidence that USN involves at least three dissociable levels of representation (roughly corresponding to Marr's 1982 model of visual processing). The main implication of this conclusion for theories of neglect is that USN clearly refers to a heterogeneous group of disorders that affect dissociable levels of processing. The implication for understanding the cognitive mechanisms that underlie normal spatial processing is that recognition of printed words and other objects with spatial extent involves the computation of at least three levels of representation with different coordinates (as originally proposed by Marr & Nishihara, 1978; Marr, 1982).

The question of whether or not the dissociable disorders of USN affecting different levels of representation correspond to separate loci of brain lesions cannot be adequately evaluated with the small number of cases reported or reviewed in this paper. However, it is interesting to note that CS and AWR, who are hypothesized to have viewer-centered USN, both had large lesions in the right middle cerebral artery distribution (temporal, parietal, and occipital) that spared much of the basal ganglia. (No scans are available for AS). A previously reported patient, BPN, with hypothesized stimulus-centered USN, had a similar lesion except that it included all of the right basal ganglia and internal capsule. NG, with hypothesized object-centered neglect, had a large parietal lesion that also extended to the basal ganglia (see Hillis & Caramazza, 1995b, for CT scans of BPN and NG).

### *Alternative Hypotheses Concerning the Levels of Representation Influenced by USN*

Other proposals have been offered regarding the coordinate frames of object processing affected by USN. These hypotheses differ from our model in two important ways: (1) the coordinate frames specified and (2) whether or not USN can affect each representation independently. Table 9 briefly summarizes how these proposals coincide and how they differ. Below we briefly describe each of these alternative proposals and discuss how the data presented for each hypothesis might be explained by our model.

Behrmann and Moscovitch (1994) proposed that USN necessarily influences processing of viewer-centered (which they also called environment-centered) and object-centered representations simultaneously. They argue that USN is a unitary disturbance that necessarily coexists in more than one frame of reference and that object-centered USN is revealed only in restricted circumstances (when the task involves stimuli with "intrinsic" left and right sides). Their conclusions were based on a series of creative experiments, in



TABLE 9  
Coordinate Frames of Representations Computed in Visual Object Recognition, as Proposed in Various Models

Authors	Level		
	First (earliest)	Middle	Final
Marr (1982)	Retinocentric	Viewer-centered	Object-centered
Caramazza and Hillis (1990a)	Retinocentric	Stimulus-centered	Object-centered
Hillis and Caramazza (1995b)			
Behrmann and Moscovitch (1994)	Viewer-centered	None	Object-centered
Behrmann and Tipper (1992)	Environment-centered		
Young et al. (1992)	?	?	Viewer-centered code of the object-itself
Farah et al. (1990)	Viewer-centered	Environment-centered	Object-centered <sup>a</sup>

<sup>a</sup> Farah et al. argue that the object-centered representation is not affected by USN (but see Hillis & Rapp, in press, for criticism of this claim based on reanalysis of their data).

which patients had to identify colors outlining drawings of objects or animals (which, they argued, do not have an intrinsic "left" side) or of letters that do have an intrinsic left side (e.g., B and K). When the stimuli were "real world objects," (e.g., animals) all their patients with USN made errors on the left side of the viewer/environment, both when the left side of the object was depicted on the left of the viewer/environment (when it was upright) and when the right side of the object was depicted on the left of the viewer/environment (when the object was rotated 180°). That is, they showed exclusively viewer-centered/"environment-centered" USN on this task. But in the same task using objects with intrinsic left and right sides (the letters R, F, and B), their patients made errors with respect to both the left of the viewer/environment *and* the left of the letter (when the letter was rotated so that its left side was on the right of the viewer/environment). That is, some of the patients showed both object-centered and viewer-centered USN on this task, leading the authors to conclude that USN simultaneously affects processing with respect to both object-centered and viewer/environment-centered coordinates. However, only four of the six patients showed object-centered neglect, whereas all six showed viewer/environment-centered neglect in the letter task—a result that can be interpreted as evidence against the necessary co-occurrence of USN in the two coordinate frames. The data presented by Behrmann and Moscovitch can be explained within the framework we have presented by proposing that: (1) All six patients had stimulus-centered or viewer-centered USN, so that they made errors on the left side of the physical stimulus/viewer (these frames were confounded in this task), and (2) four of the six patients also had object-centered USN, so that they made errors on the left side of objects with intrinsic sides even when it was in the right side of the viewer/environment. Likewise, Tipper and Behrmann, 1996 have shown that some patients show both object-centered USN and "location-based" (retinal-/head-/body-centered) USN, whereas others show USN in just one of these frames.

A similar proposal of two coordinate frames of USN has been offered by Young et al. (1992). They reported a patient, BQ, who failed to identify (or detect differences in) the left side of chimeric faces composed of the left side of one person's face and the right side of another person's face. BQ made errors on the left side of chimeric faces at the same rate even when the face was presented to the right visual field in tachistoscopic tasks (so the errors were not specific to the left visual field). But when the chimeric face was inverted, BQ made errors in identifying the right side of the face, which was now the left side of the stimulus. BQ's performance can be neatly accounted for by proposing that her USN arose at the level of a stimulus-centered representation. That is, her errors were specific to the left side of the stimulus, irrespective of its location with respect to the viewer and irrespective of which side of the object (the chimeric face) was depicted on the left side of the stimulus. This performance mirrors the reading performance

attributed to a deficit at the level of a stimulus-centered representation: errors on the left side of the stimulus, even when the stimulus word falls in the right visual hemifield, and even when the left side of the stimulus is the right side of the object (the final letters of the word) (Hillis & Caramazza, 1991; Nichelli et al., 1993). Furthermore, a comparable pattern of performance on upright and inverted chimera was shown by patient BPN, whose reading performance was also attributed to stimulus-centered USN (Hillis & Caramazza, 1995b). Although Young and coauthors did not specifically interpret BQ's errors as the result of left stimulus-centered USN, they admitted that her neglect "did not operate in what in Marr's (1982) terms would be object-centered coordinates (since she continued to neglect the side of inverted faces falling to the left). . . . [and] the neglect coordinates were not retinal; left side neglect was found even to stimuli that had fallen only on the visual field" (p. 68). The authors proposed instead that BQ's USN affected "a viewer-centered code of the object itself."<sup>2</sup>

Young et al. (1992) also reported that BQ made fewer errors in identifying the left half-face in a chimera when there was a gap between the left and right half-faces. Buxbaum and Coslett (1994) reported the same pattern in 5/22 patients they tested with USN. Considered by itself, this result is consistent with the proposal that USN of these patients did not involve a viewer-centered representation (since in the gap condition the left half-face was actually further to the left of the viewer and the visual field), but concerned either an object-centered or a stimulus-centered representation (since in the gap condition, the two half-faces might be recognized as two separate stimuli or objects). In the case of BQ the fact that she made errors when the chimera was inverted on the left side of the stimulus (the right half-face) allows us to rule out object-centered USN. There should be no effect of the orientation of the stimulus for patients with object-centered neglect. However, performance on rotated stimuli was not reported by Buxbaum and Coslett, so the USN of these patients might have concerned the stimulus-centered and/or the object-centered levels of representation. The fact that this pattern was observed in only 5 of the 22 patients with clinically diagnosed "neglect"

<sup>2</sup> However, this is not entirely an accurate characterization of BQ's deficit, since she did not make errors recognizing left half-faces presented in isolation (which would still be the left half of the "object-itself"). That is, if her USN affected the left side of "viewer-centered code of the object-itself" she should make errors at the same rate on the left half-face whether it is presented in isolation or in the chimera. In contrast, if BQ's deficit affected the left half of the stimulus-centered representation, we would expect more errors on the left half-face in the chimera than on the left half-face presented alone. This result is predicted because in the former condition (the left half-face in the chimera) the entire left half of the face would constitute the neglected side of the stimulus, whereas in the latter condition (the left half-face presented alone), only about one quarter of the face—the left half of the half-face—would constitute the neglected side of the stimulus. Thus, more of the left half-face would be adequately processed when the left half is presented alone, rather than in the chimera. Therefore, their results were consistent with the prediction of hypothesized stimulus-centered USN.

provides further evidence that USN is a heterogeneous disorder that can affect a given level of representation (in this case, the object- and/or stimulus-centered level) in some patients and not others. A similar conclusion was drawn by Coslett (1989 and submitted), on the basis of a double dissociation between neglect in vision (standard tests of visuospatial neglect) and neglect in visual imagery (neglect of the left side of an imagined array).

Humphreys and Riddoch (1994) also presented evidence that USN can independently affect two forms of spatial representation. They reported two patients, EL and JR, who each made errors predominantly on the left side in some tasks (e.g., reading individual words, identifying pictures, bisecting lines) and made errors predominantly on the right in other tasks (e.g., line cancellation, identifying words scattered across the page, naming individual letters in words). They interpreted the pattern of performance of these two patients as evidence for left USN in processing representations that specify the spatial relations between parts of a single object and right USN in processing representations that specify spatial relations between multiple objects. Although this interpretation of the reported pattern of performance may be the correct one, it is also subject to at least one alternative account (as outlined below). The reported pattern of performance is not (as the authors suggest) problematic for the model we have presented, although some aspects of performance require that we propose a unilateral impairment that is outside the scope of our model of word/object recognition.

One account of JR's and EL's pattern of performance that is consistent with the proposals in this paper follows. We propose (in accord with the authors) that each patient had two independent forms of USN affecting two distinct types of spatial representation. Their left-sided errors within objects might be accounted for by left stimulus-centered USN. This deficit would account for the reported left-sided errors in reading words, copying words, omissions in cancelling lines on the left side of each "strip" of lines on a page, and errors identifying pictures when salient features were on the left, since in each case, errors occurred on the left side of an individual stimulus. It would also account for the relatively few left-sided errors in oral spelling, since the task of oral spelling does not require the computation of a stimulus-centered representation. JR's and EL's right-sided errors in tasks requiring movement between objects can be accounted for by assuming right USN in representations that drive exploratory movements (a representation and process that is outside the scope of the model of word/object recognition that we have presented). This additional deficit would account for the patients' right-sided omissions in naming individual letters of words, copying words, and cancelling lines distributed across a sheet of paper.

### *Other Explanations of Left-Sided Errors*

We have accounted for the pattern of performance of AWR by proposing USN at a viewer-centered, retinotopic level of representation. However,

the fact that AWR had homonymous hemianopia (evidenced by Humphreys perimetry testing) raises an important question. Could AWR's visual field cut alone account for her retinotopic deficit in reading and nonlexical tasks? More generally, could the patterns of performance we reported result from homonymous hemianopia in some patients and USN in other patients?

There were some differences between AWR and the other patients which might be attributable to homonymous hemianopia, either alone or in addition to viewer-centered USN. These aspects of performance include (1) a relatively low rate of errors in standard reading compared to tachistoscopic reading and (2) below chance performance on the tachistoscopic letter detection task at all positions to the left of fixation, in contrast to a gradual decline in accuracy levels across the left hemifield (as shown by CS). Nevertheless, other aspects of AWR's performance are not easily explained by a left visual field cut alone. First, she continued to make some errors in reading single words 6 years after her stroke, whereas other patients with homonymous hemianopia, like SWR, learn to compensate perfectly well for the same type of deficits within a few months (as reported by Binder & Mohr, 1992; but see Zihl, 1995). Similarly, AWR made gross omissions on the left in copying scenes and gross errors in line bisection, even after she correctly marked the end of each line. Like reading, performance on these tasks is ordinarily spared in the presence of chronic homonymous hemianopia alone (Chedru, 1976). SWR also showed normal performance on these tasks.

### *Conclusions*

In this paper we reported the performance of three patients with unilateral, right hemisphere strokes who made errors specific to the side of the viewer's space (relative to the center of the retina, head, and/or body) contralateral to brain damage. We contrasted their pattern of performance to previously reported patterns of errors specific to the side of the physical stimulus and errors specific to the side of the object contralateral to brain damage, using the same tasks. In two of the three patients in this study the hemispacial deficit occurred in the absence of a primary deficit in sensory input. Furthermore, we showed that performance of the patient with homonymous hemianopia as well as USN stood in marked contrast to performance by a control subject with homonymous hemianopia without USN. Together, these data provide evidence that USN affecting a viewer-centered level of representation can occur independently of USN affecting a stimulus-centered or an object-centered level of representation. The fact that AWR's performance on additional tasks was explicable by proposing retinotopic, rather than head-centered or body-centered coordinates, was consistent with the proposal that USN can affect any of the three levels of representation in the model of visual object representation that we have adapted from Marr (1982).

## APPENDIX

# Examples of Errors in Reading by Patients with Proposed Damage at Various Levels of Representation

Standard print: Object-centered	Stimulus-centered	Viewer-centered
NG <sup>a</sup> status → statue rang → range planet → plane chin → chew sparrow → spared hound → house		
HB <sup>a</sup> pill → pillow save → saved axe → axil sailing → sailed hound → house passed → pass	BPN balloon → spoon leaf → deaf clock → rock flower → power dove → stove doll → roll	AS ideal → steal bridges → ridges theater → eater tread → read ledge → hedge cloves → loves
ML gull → dull rust → bust rave → brave glove → love hard → card reply → apply	RW broad → road paid → said borough → through sought → drought proven → woven member → remember	AWR theater → heater tripped → stripped chow → show fail → sail gut → out grow → throw
JL deserve → observe tractor → doctor know → now fled → sped hastily → gastily bequeath → queath	GG mezzaluna → una margine → vergine dio → stupendio	CS tripped → dropped picked → backed tight → light mashing → smashing found → round pouch → ouch

<sup>a</sup> Left hemisphere lesion.



APPENDIX (*Continued*)

Errors in mirror-reversed reading:

Object-centered <sup>a</sup>	Stimulus-centered <sup>b</sup>	Viewer-centered
LHD	RHD	RHD
Predicted: Errors on final letters (contralesional)	Errors on final letters (ipsilesional)	Errors on final letters (ipsilesional)
NG	BPN	CS
common → comet	hang → ham	lick → licked
join → joint	lard → lake	pocket → pocker
greenish → greenery	hear → heal	tough → touch
discovery → disco	roof → roger	upstage → upstate
regulated → regular	stab → states	nightgown → night something
dashes → dash	bark → bar	AS
RHD	dean → deaf	should → shoulder
Predicted: Errors on initial letters (contralesional)	chef → chill	strange → strand
ML	wood → wool	shall → share
sleek → leek	fail → fast	status → statue
sincere → insincere	bask → base	bought → bough
village → ill-age	RW	friend → fry
urban → ran	severe → seven	basis → basic
suspend → spend	though → thought	AWR
	bole → bold	provide → provider
	angry → anger	
	thousand → though	
	absence → absent	

<sup>a</sup> HB (Hillis & Caramazza, 1995a) and JL (Barbut & Gazzaniga, 1987) were not tested on mirror-reversed print.

<sup>b</sup> Although GG (Nichelli et al., 1993) was reported to make errors on the final letters (ipsilesional) in reading mirror-reversed print, no examples were reported.

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