Object-Centered Neglect in Patients with Unilateral Neglect: Effects of Left–Right Coordinates of Objects

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Abstract

■ When patients with right-sided hemispheric lesions neglect information on the left side, with respect to what set of spatial coordinates is left defined? Two potential reference frames were examined in this study, one where left and right are defined with respect to the midline of the viewer and/or environment (viewer/env-centered) and the other where left and right are defined with respect to the midline of the object (object-centered) By rotating the stimulus 90° clockwise or counterclockwise, and instructing patients with neglect to report the colors appearing around the border of a stimulus, an independent measure was obtained for the number of colors reported from the left and right of the viewer/env- and from the object-based reference frame. Whereas significant object-centered neglect was observed only for upper case asymmetrical letters but not for symmetrical letters nor for drawings of familiar animals or objects, significant viewer/env-based neglect was observed with all the stimulus types We present an account of the coexistence of neglect in more than one frame of reference and the presence of object-centered neglect under a restricted set of conditions ■

INTRODUCTION

Unilateral or hemispatial neglect is a neurobehavioral deficit in which patients fail to report or to orient to information appearing on the side of space contralateral to the side of the lesion. Neglect is more frequent and more severe after right hemisphere damage, particularly to the inferior parietal lobule (Colombo, De Renzi, & Faglioni, 1976; Bisiach, Cornacchia, Sterzi, & Vallar, 1984; but see Ogden, 1985), but it may also occur after damage to other cortical and subcortical structures (Bisiach & Vallar, 1988; Heilman, Watson, & Valenstein, 1985; Mesulam, 1981; Vallar & Perani, 1986) In personal care, patients with left-sided neglect following right hemisphere damage may not shave or dress on the left side and may not eat food on the left side of the plate In processing extrapersonal sensory information, they may ignore visual, auditory or tactile information that is presented to their contralesional side, and even in their imagined internal representations they may not report information appearing on that side (Bisiach & Luzzatti, 1978)

Several explanations have been proposed to account for the mechanism underlying the neglect phenomenon Whereas there is currently general agreement that the fundamental deficit is one of a disruption of attention, the particular form of the deficit remains controversial (Bisiach, 1993) One view suggests that, following right hemisphere damage, patients may have difficulties disengaging attention from one location in order to move it to a new location (Posner, 1988; see also Rizzolatti & Berti, 1990) An alternate view suggests that attention may be distributed more optimally to the right than to the left side (D'Erme, Robertson, Bartolomeo, Daniele, & Gainotti, 1992; Kinsbourne, 1987; Ladavas, Petronió, & Umilta, 1990; Robertson, 1992) Irrespective of the exact form of the attentional deficit, one question that remains unanswered in all attentional accounts is with respect to what coordinate system or frame of reference are "left" and "right" defined Though posed in relation to neglect patients, this question has implications for understanding the distribution of attention in normal people

There are a number of potential frames of reference that can be used to code left and right (Feldman, 1985; Hinton, 1981) and, recently, there have been several attempts to examine the question of frame of reference in patients with unilateral neglect Some recent studies, for example, have shown that neglect patients ignore information appearing on the left where the frame of reference is defined by a plane through the viewer's midline (either through the head or trunk, collectively referred to as *viewer-centered neglect*) Thus, information appearing to the left of the midline of the viewer is reported more poorly than information appearing to the viewer's right (Calvanio, Petrone, & Levine, 1987; Farah,

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Brunn, Wong, Wallace, & Carpenter, 1990; Karnath, Christ, & Hartje, 1993; Karnath, Schenkel, & Fischer, 1991; Ladavas, 1987) A second set of reference axes within which neglect may arise is that which is defined with respect to the environment or scene and several studies have shown that patients with neglect omit more information on the left than on the right within this frame of reference (*environment-centered neglect*) Moreover, many studies have suggested that neglect arises with respect to *both* viewer and environmental coordinates In these studies (Calvanio et al , 1987; Gazzaniga & Ladavas, 1987; Ladavas, 1987), patients with left neglect perform a task in two conditions: when seated either with their heads upright or with their heads tilted 90° to the left or right The results from these studies revealed that the patients were less efficient at picking up stimuli from the left than from the right in the first condition (head upright) Since the left of viewer-centered and of environment-centered coordinates coincide in this condition, it is not possible to determine whether neglect is occurring within one or within both of these frames of reference In the head-tilted condition, however, the frames of reference are decoupled; the stimuli remain horizontally oriented in environmental coordinates but fall within the same field in viewer coordinates when the head is rotated 90° Interestingly, under the head-tilted condition, the patients were still poor at picking up the stimuli that occupied the left side as defined in environmental coordinates In addition, these patients were also worse at picking up information appearing on the left than on the right of the body midline when their heads were rotated These findings suggest that both viewer and environmental coordinates play a role in determining the frame of spatial representation for neglect and lend support to the view that visuospatial attention is distributed in more than one set of spatial coordinates

In addition to viewer- and environment-based coordinates, spatial coding of visual information can occur with respect to yet another set of coordinates, those centered on the object itself (Marr, 1982; Marr & Nishihara, 1978) According to this view, a reference axis for an object is determined on the basis of the symmetry or axis of elongation of the object The object-centered frame is aligned with this reference axis and, then, the arrangement of the object's parts is described in relation to this midline axis (Marr, 1982; Marr & Nishihara, 1978) In this way, features of an object are encoded according to a set of coordinates centered on or intrinsic to the object itself (see also Humphreys, 1983; Plaut & Farah, 1990) Within this *object-based* reference frame, left and right are defined with respect to the object itself—for example, the number 9 on a clock is still represented as being on the left and the number 3 on the right even when the clock is displaced from its canonical orientation This form of coding is particularly advantageous since it affords structural invariance to objects across different orientational transformations If visuospatial information is indeed coded in an object-based frame and attention is deployed within this frame, then one might expect to see neglect of information on the left where left is defined with respect to the midline of the perceived object In the case of the clock, then, even when the clock is rotated 180°, such that the 9 lies on the right side of space (patient's ipsilesional side) but on the left side of the object, one might still expect to see neglect of the number 9

At present, evidence of *object-centered neglect* has been reported in only a few studies Perhaps the most dramatic demonstration of the object-based effect to date comes from Driver and Halligan (1991) They tested their subject, PP, on a same–different judgment task using vertically elongated nonsense shapes that were bottom-heavy When the two stimuli were different, the point of difference appeared with equal probability on the left and right of the stimulus The stimuli were presented in two conditions, either upright, in which the two stimuli were both vertically oriented (where left of the stimulus coincided with the left from the viewer's perspective), or both tilted 45° In this latter condition, the viewer- and object-based frames are placed in opposition—the point of difference between the stimuli might fall on the left with respect to the object itself but on the right side of space from the viewer's perspective PP was significantly poorer at detecting the difference on the left than on the right of the object in the upright condition She was also significantly poorer at detecting the difference on the left than on the right of space (defined by PP's sagittal midline) in the tilted condition The major finding, however, was that she still failed to detect the point of difference when it fell on the left of the object even when the critical information was now on the patient's egocentric right These data suggest that neglect occurs not only for information in left space but also for information appearing on the left of the object independent of its spatial location

Additional affirmative evidence favoring neglect in object-centered coordinates comes from Young, Hellawell, and Welch (1992) Using chimeric faces, they showed that their patient, BQ, was unable to identify any of the chimera on the left when the display was upright When the display was rotated 90°, BQ still failed to recognize on 8/20 trials what would have been the left side if the faces had been upright In contrast, she performed correctly on all chimeras that would have been the right sides of faces The fact that BQ performs poorly on left-sided chimeric faces even when they no longer occupy the left of space suggests that neglect may arise within a more abstract description centered on the object itself Finally, object-based neglect has been reported not only for objects but also for words Caramazza and Hillis (1990a,b) showed that their right-neglect patient, NG, made errors in reading the right ends of words (e g , PEARL → "PEAR") irrespective of whether the words were presented in horizontal, vertical, or mirrorreversed orientation This word- or object-centered deficit suggests that the underlying impairment affects the processing of information following the coding of letter position relative to the stimulus itself, i e , once the object-centered frame is established In addition to this object-centered effect, NG also performs more poorly for information on the right defined by the scene or environment relative to the left—in detecting the presence or absence of a gap on the right side of a single circle, she makes more errors as the circle is displaced to the right of space (Hillis, 1993) Although these studies (Caramazza & Hillis, 1990a,b; Driver & Halligan, 1991; Hillis, 1993; Young et al , 1992) use different methods and stimuli, they all demonstrate that neglect can arise within a higher order, abstract coordinate frame It is important to note, however, that in all cases, neglect of contralesional information where left and right are defined by the intrinsic midline of the object did not occur in isolation In addition to this object-centered neglect, information on the contralesional side defined extrinsically, i e , in a viewer-centered reference frame and/or an environmental frame, was also neglected

Despite the evidence favoring object-centered neglect, not every study has produced affirmative findings In a study using black and white line drawings of familiar animals or objects (e g , rabbit) with 10 neglect patients, Farah et al (1990) did not find object-centered neglect In this study, the patients were required to report the identity of 16 single letters that were distributed randomly over the internal four quadrants of the object defined by the boundaries of each drawing The number of letters reported was calculated separately for each quadrant As in previous studies, the subjects performed the task in a number of conditions, only two of which are relevant for the present purposes: (1) *upright*—when the viewer was seated upright and the stimulus was also upright and (2) *tilted*—when the viewer was seated upright but the stimulus was tilted 90° counterclockwise or clockwise (see Fig 1)

As can be seen in Figure 1, in the *upright* condition, letters appearing in quadrants 1 and 4 fall on the left defined by the viewer-, the environment-, and the object-centered frame Because these three frames are all aligned, it is impossible to examine the relative contribution of each frame individually When the objects are rotated as in the *tilted* condition, however, it is possible to obtain an assessment of the object-based effects independent of the other frames of reference Here, letters appearing in quadrants 1 and 4 and in quadrants 2 and 3 fall to the left and right of the midline of the viewer and the environment More importantly, letters falling in quadrants 3 and 4 (counterclockwise rotation) and 1 and 2 (clockwise rotation) fall to the left of the object-centered midline, while those in quadrants 1 and 2 (counterclockwise rotation) and 3 and 4 (clockwise rotation) fall to the right Because the quadrants on the left of the viewer are not identical to those on the left of the object, an independent measure of the neglect in the two reference frames may be obtained The prediction is that if neglect does arise in object-centered coordinates, then identification should be poorer for letters falling on the left compared to the right where left and right are defined in intrinsic object-centered coordinates Farah et al (1990) showed that significantly fewer letters were reported from the left compared to the right side in the *upright* condition In the critical *tilted* condition, however, there was no significant difference between the number of letters reported from the left and right of the rotated stimulus where left and right are defined with respect to a central axis aligned with the object itself These findings suggest that neglect does not arise within an object-centered reference frame Rather, they favor the view that neglect arises within an extrinsic frame of reference centered either on the viewer or on the environment or on both

There are several possible explanations for Farah et al 's null finding One possibility is that the nature of the task did not require the patients to make use of the object-centered frame when instructed to report the letters (see Rock, 1990, for discussion of "task appropriate frames") Because the patients concentrated on the individual letters rather than on the object itself, it was not necessary for them to maintain the object reference frame; instead, the patients could simply ignore the "background" object A further reason for the absence of the effect is that object-centered neglect may arise only under those conditions in which it is possible to establish a principal axis or axis of elongation (Driver & Halligan, 1991) When left and right are defined with respect to this central reference axis, then neglect for the left or right of the object's midline may be observed Therefore, it is possible, that although Farah et al (1990) did not find an overall object-centered effect, it may have existed for a subset of the items used in that study, i e , those that are vertically oriented and have a longitudinal axis Since these vertically oriented items (e g , gorilla, tree) were not analyzed separately from the other items, the question regarding the axis of elongation remains unanswered The purpose of the present investigation, then, is to explore further the mechanisms mediating object-centered neglect and to evaluate under what conditions object-centered neglect may be observed Results from such studies will shed light on the mechanism of attention and the frame of reference in which it is distributed during visuospatial processing

EXPERIMENT 1: OBJECT-BASED NEGLECT USING REAL WORLD OBJECTS

The first experiment was designed to examine whether neglect for the left of an object may be observed when the object frame is made more relevant and integral to the task, than it was in the study of Farah et al (1990) Instead of reporting letters, subjects were instructed to

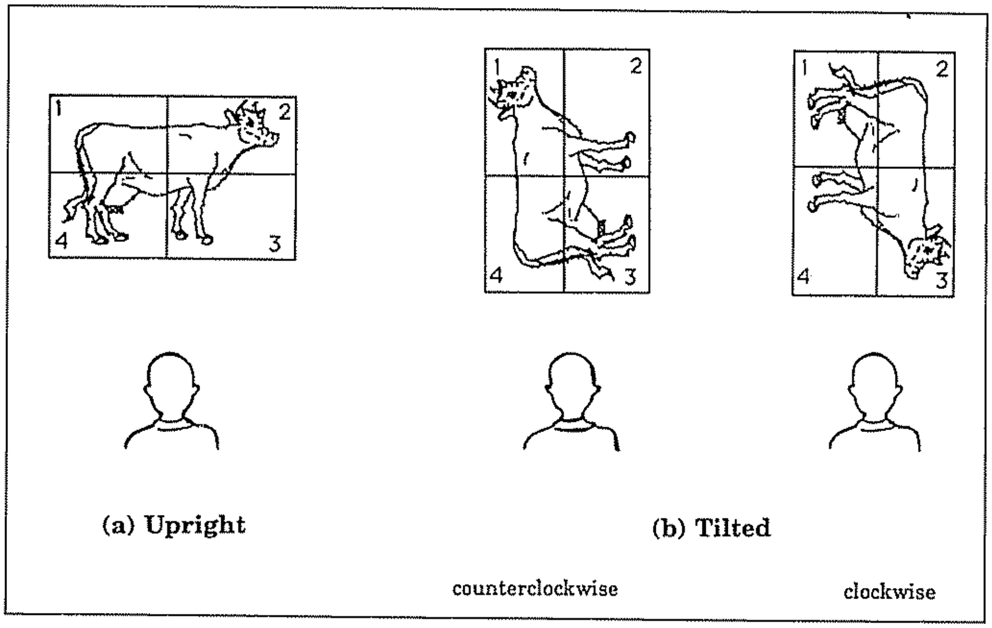


Figure 1. Depiction of relation between viewer and object: (a) upright—viewer and object upright, (b) tilted—viewer upright, object rotated counterclockwise and clockwise

pay attention to the outline of drawings and to report the colors drawn around the boundaries of the drawings of familiar real world objects and animals The subjects reported the colors of the drawings in both the *upright* and *tilted* conditions as shown in Figure 1 The numbering of quadrants used throughout this paper refers to the numbers depicted in Figure 1 Comparisons were made between the number of colors reported from quadrants appearing on the left and on the right of the viewer- and environment-centered frames in the upright and tilted conditions. Thereafter, a comparison between the number of colors reported from the left and right of the object-based frame of reference was carried out

Results

No subject made any errors in recognizing the objects Figure 2 shows the mean percentage colors reported correctly in the *upright* condition across the five neglect patients from the left (quadrants 1 and 4) and the right (quadrants 2 and 3) when all the reference frames are aligned. As expected for patients with left-sided neglect, significantly fewer colors were reported from the left of the display (mean 93 6; 59%) than from the right (mean 142 2; 89%) [$t(4) = 7.5, p < 0.005$]

Figure 3 shows the mean percentage of colors reported in the *tilted* condition from the left and right of viewer/env coordinates and from the left and right of object-centered coordinates. In the *tilted* condition, significantly fewer colors were reported from the left (quadrants 1 and 4) (mean 219; 69%) than from the right (quadrants 2 and 3) (mean 284; 89%) [$t(4) = 4.1, p < 0.05$] where left and right are defined in viewer/env coordinates These findings are consistent with left-sided neglect Of most interest, however, is that there was no significant difference between the number of colors reported from the left (quadrants 3 and 4 counterclockwise and quadrants 1 and 2 clockwise) (mean 253; 79%) and the right (mean 258; 78%) where left and right are defined with respect to an object-based frame [$t(4) = 0.87, p > 0.05$] These results suggest that neglect does not arise for information on the left where left is defined by the frame of reference centered on the object's midline

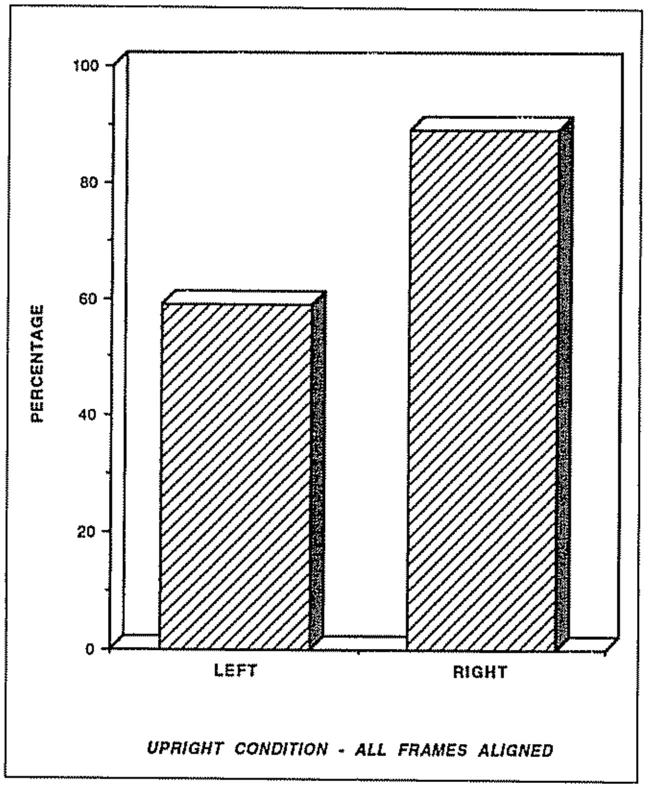


Figure 2. Mean percentage correct report of colors from left and right of drawings in the upright condition

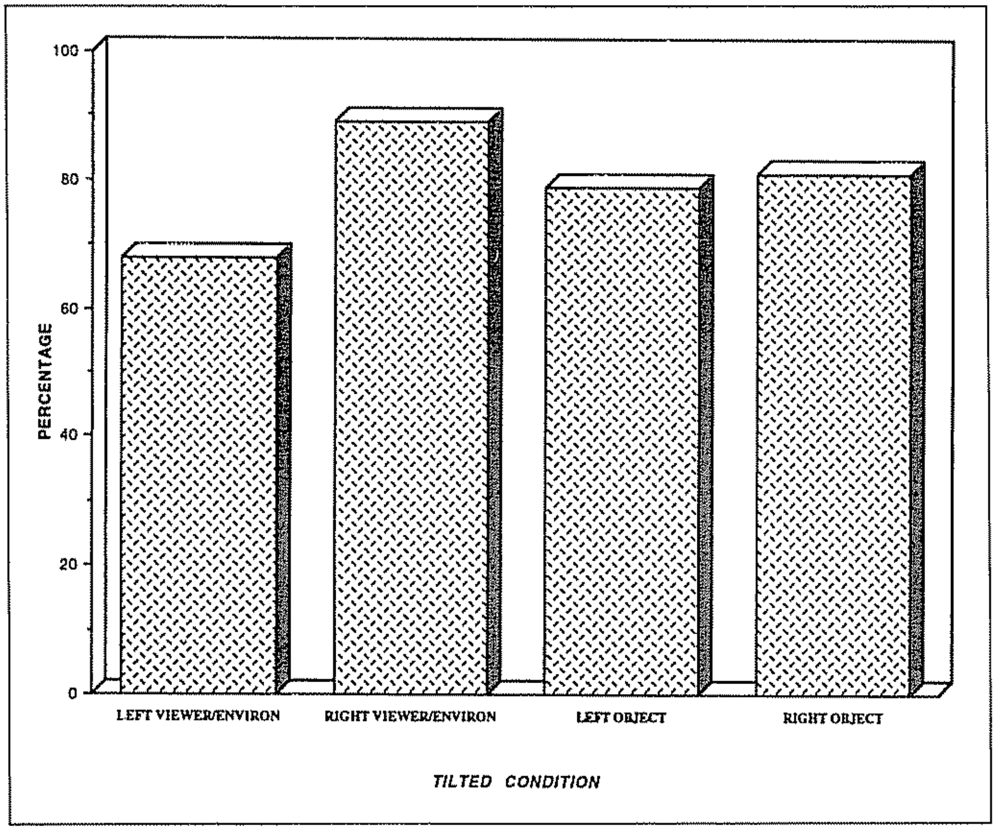


Figure 3. Mean percentage correct report of colors from left and right of drawings defined in viewer/environmental coordinates (first two bars on the left) and in object coordinates (two bars on the right) in the tilted condition

These findings, however, demonstrate only that there is a main effect of viewer/env- but not of object-centered coordinates on neglect but do not examine whether there are any joint effects of the two variables To examine the variables simultaneously, a two-way analysis of variance was carried out with viewer/env (abbreviated as V) (left/right) and object (abbreviated as O) (left/right) as within-subject variables (LVLO, LVRO, RVLO, RVRO) The eight quadrants (four clockwise, four counterclockwise) in the tilted condition were classified into the 2 × 2 table In one analysis, the data from the tilted condition alone were included and on a second analysis, the data from the upright condition were also included with quadrants 1 and 4 falling into the LVLO cell and quadrants 2 and 3 falling into the RVRO cell Because, in this latter condition, the number of data points in the LVLO and RVRO exceed those in the LVRO and RVLO cells, the cells were equalized by dividing the number correct in LVLO and RVRO by 4 and the number correct in LVRO and RVLO by 2 In both the tilted alone and the tilted + upright analyses, there was only a significant effect of V [tilted alone $F(1,4) = 18.4$, $p < 0.05$; tilted + upright $F(1,4) = 12.8$, $p < 0.05$] Neither the main effect of O nor the interaction between V and O was significant on either analysis, confirming the findings described above

Although there is no significant effect on performance of object-centered coordinates, it is still possible, that object-centered neglect may occur for the subset of objects that has a clear vertical axis of elongation as suggested by Driver and Halligan (1991) To determine whether this was the case, the data were reanalyzed by dividing the 20 drawings into three groups: those that were vertically elongated (e g , gorilla, sailboat, tree, well; $n = 6$), those that were horizontally elongated (e g , camel, cow, iron, wagon; $n = 11$) and those that were of equal horizontal and vertical extent (e g , telephone, elephant, kettle; $n = 3$) The number of colors reported by the subjects for the left and right of the object-based frame in the *tilted* condition was compared as a function of axis of elongation The results revealed no significant difference between the number of colors reported from the left and right for any of the stimulus groups [vertical $F(1,4) = 4.2$, $p > 0.10$; horizontal $F(1,4) = 6.4$, $p > 0.05$; equal $F(1,4) = 0.35$, $p > 0.5$] although the data from the horizontal elongation show a trend in the right direction

The results thus far suggest no significant difference in the number of colors reported from the left and the right of objects These data also demonstrate that this finding holds across all objects independent of the axis of elongation One remaining possibility that has not been explored is whether the object-centered effect might be observed only when the object is oriented toward or faces a particular direction For example, when the drawings of the animals were presented, on half the trials, the animals faced left and on the remaining half, they faced right To determine whether there was any effect of the direction in which the animals were pointing, a post hoc analysis was conducted comparing the number of colors reported from the left and the right defined in object-centered coordinates in the *tilted* condition for animals that would have been facing left and for animals that would have been facing right prior to rotation (see Fig 1 for example of animal facing right) A prediction might be that when the head of the animal is facing left, even when it is tilted, attention might be drawn over to the head and there would be no difference in the number of colors reported from the left and the right defined in object-centered coordinates When the animal is facing right, however (as in Fig 1), the reverse might hold The results again revealed no significant difference in the number of colors reported from the left and the right in object-centered coordinates for animals facing left or for animals facing right [facing left $F(1,4) = 0.63, p > 0.1$; facing right $F(1,4) = 0.3, p > 0.5$]

Discussion

A major finding from Experiment 1 is that information appearing on the left side is neglected more than information on the right side where left and right are defined by coordinates extrinsic to the object, i e , by environmental and/or viewer-centered coordinates This result is consistent with those of a host of studies that have argued that visuospatial information is distributed according to a set of spatial coordinates centered on the environmental or viewer perspective (Calvanio et al , 1987; Farah et al , 1990; Karnath et al , 1991, 1993; Ladavas, 1987) A second important finding is that there is no significant left-sided neglect where left is now defined within an object-centered frame Furthermore, neither the axis of elongation of the drawing (vertical, horizontal, equal) nor the direction in which the drawing is facing (left, right) has any influence on the object-centered effect These results argue against the presence of neglect in an object-centered frame of reference and suggest that visuospatial attention is not distributed according to spatial coordinates that are intrinsic to the object

Previously, we had argued that object-based effects may not be apparent in tasks where the object-based frame was irrelevant to performing the task such as in the study by Farah et al (1990) In Experiment 1, we attempted to circumvent that problem by having subjects report the colors that formed the outlines of the drawings Despite this attempt, the failure to demonstrate an object-centered effect in the present study may also be that reporting colors, like reporting letters, does not demand the use of the object-based frame Another possibility, however, is that it is not the nature of the task that is the problem but rather that the stimulus material is not conducive to producing object-based neglect The familiar objects and animals used in Farah et al (1990) and in Experiment 1 do not have a definitive intrinsic left or right side—a cow may face left or it may face right Because there is no canonical handedness for these objects, when looking at a picture of a cow, left and right are simply coded by default from the extrinsic perspective of the viewer during perception As such, object-centered coordinates are not involved in initial coding Since left and right are not inherent to the representation of these objects, assigning left–right coordinates to the drawing simply depends on the viewer's perspective One hypothesis, then, is that object-centered effects might arise only when there is a canonical asymmetry to the objects; under these conditions, the left and right of the object must be specifically marked and maintained to ensure the proper representation of the item If this is the case, then, one might expect that the distribution of attention is influenced by an object-centered reference frame when the objects are inherently asymmetrical and an intrinsic principal axis is required to maintain the canonical representation

The number of real world items that have the property of intrinsic handedness is small One example of this kind of item is the hand—the left hand remains the left hand irrespective of the orientation or position of the hand or body (see Kant, 1929, for discussion of intrinsic asymmetry of hands) One study using hands as stimuli with neglect patients has been reported Although this study was designed to examine the role of body image in neglect rather than the reference frames for neglect, the evidence is still pertinent In this study, Coslett (1989) showed that, when a patient with neglect was required to match pictures of left and right hands presented in different orientations, he was able to match pictures of the right hand significantly better than those of the left Since the identity of the left hand is preserved irrespective of the current orientation of the hand, and an object-centered frame is essential for determining this identity, these data are consistent with object-based neglect The prediction, therefore, is that object-based neglect may be observed only for stimuli that have an intrinsic left–right handedness and for which an object-based frame is salient and necessary for maintaining this canonical asymmetry

EXPERIMENT 2: OBJECT-BASED NEGLECT IN ASYMMETRICAL LETTERS

This experiment was designed to examine whether object-based neglect occurs for stimuli that have an inherent asymmetry or handedness Asymmetrical letters have a predefined left and right side; for example, the letter *B* has a principal axis dividing it into left and right halves and this axis must be maintained in order to derive the proper representation of the letter If intrinsic handedness is critical, then we might expect to see object-based neglect for asymmetrical letters of the alphabet The design of this experiment was identical to that of Experiment 1 except that asymmetrical upper-case block letters of the alphabet were used rather than drawings of real world objects and animals

Results

No errors were made in identifying any of the letters Figure 4 shows the mean percentage of colors across the seven subjects reported from the left and the right of the asymmetrical letters in the *upright* condition

Significant left-sided neglect was observed when the viewer and stimulus were both upright A mean of 40 (out of 80 colors; 50%) was reported from the left (quadrants 1 and 4) compared with a mean of 69 from the right (quadrants 2 and 3; 86%) [$t(6) = 6\ 32, p < 0\ 001$], confirming the presence of left-sided neglect in these subjects When the letters were rotated as in the tilted condition (Figure 5), significantly fewer colors were still reported from the left than the right where left was defined with respect to viewer/env coordinates A mean of 110 colors (maximum is 160; 69%) and 138 (87%) was reported from the left (quadrants 1 and 4) and the right (quadrants 2 and 3), respectively [$t(6) = 3\ 09, p < 0\ 05$]

When object-centered coordinates are considered (see Fig 5), significantly fewer colors were reported from the left (quadrants 3 and 4 counterclockwise and quadrants 1 and 2 clockwise) (mean 106; 66%) than from the right (mean 141; 88%) [$t(6) = 9\ 9, p < 0\ 001$] An examination of the individual data shows that all seven subjects reported fewer letters from the left than from the right of the object

An analysis of variance, using the same procedure as in Experiment 1, was conducted to examine the joint effects of the viewer/env and object variables on performance, with one analysis using data from the tilted condition alone and the second analysis including the data from the upright condition with the cells equalized While in both tilted and tilted + upright analyses main effects of viewer-env- and object-centered coordinates were observed, an interaction between them was also noted in the tilted + upright analysis [$F(1,6) = 39\ 8, p < 0\ 001$] Because more data are included in the tilted + upright analysis than in the tilted analysis alone, it is possible that when the statistical power is increased, the interaction is revealed

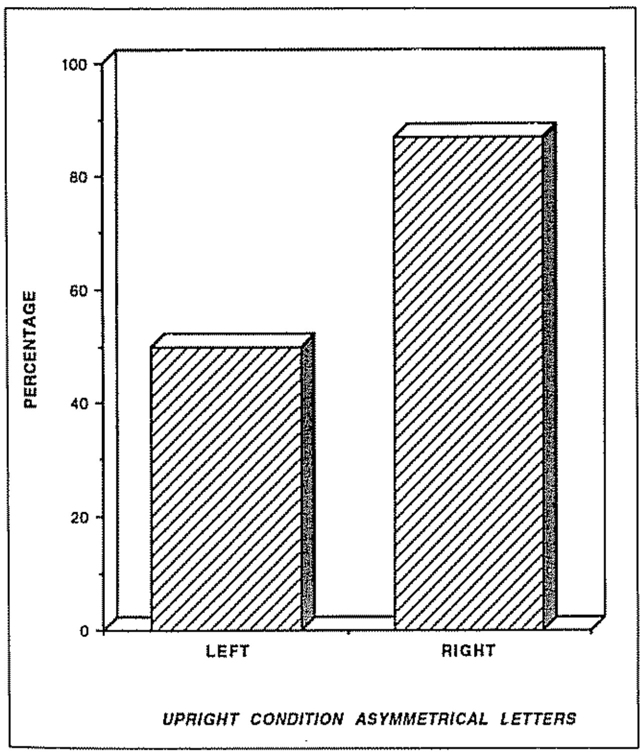


Figure 4. Mean percentage correct report of colors from left and right of asymmetrical letters in the upright condition

Discussion

The results from this experiment support those of Experiment 1 in demonstrating that neglect arises when attention is distributed in a frame of reference centered on the viewer or on the environment or on both In addition, however, this experiment, unlike Experiment 1, provides evidence supporting the presence of object-centered neglect, with poorer report of left- than right-sided information where left and right are defined in object-centered coordinates Furthermore, there is an interaction such that disproportionately fewer letters are reported from the left defined both by viewer/env and by object coordinates relative to all other conditions The joint contribution of more than one frame of reference in the distribution of attention has been observed by Tipper, Weaver, Jerreat, and Burak (1994) Using an inhibition of return (IOR) paradigm, they showed that normal subjects are slower to detect the presence of a target that appears in a previously cued location relative to an uncued location (IOR in viewer/env coordinates) and that subjects are also slower at detecting the target when it appears in a previously cued object relative to an uncued object independent of the location of the object (IOR in object-centered coordinates) Furthermore, there is an interaction such that detection of a target is disproportionately slowed when the target appears in both a previously cued object and spatial location

That one can get object-centered effects at all using the color-reporting task indicates that the absence of object-centered neglect in Experiment 1 cannot be attributed to the task per se Rather, these findings suggest that the presence and absence of the object-centered effect are tied to the nature of the stimuli When the stimulus has a left–right handedness that must be maintained through a central axis, it is possible to observe object-based neglect Because the asymmetrical letters used in the experiment have an inherent left–right difference, the left and right of the object must be marked and differentiated so that the proper representation of the two sides is maintained Once the principal or mid-

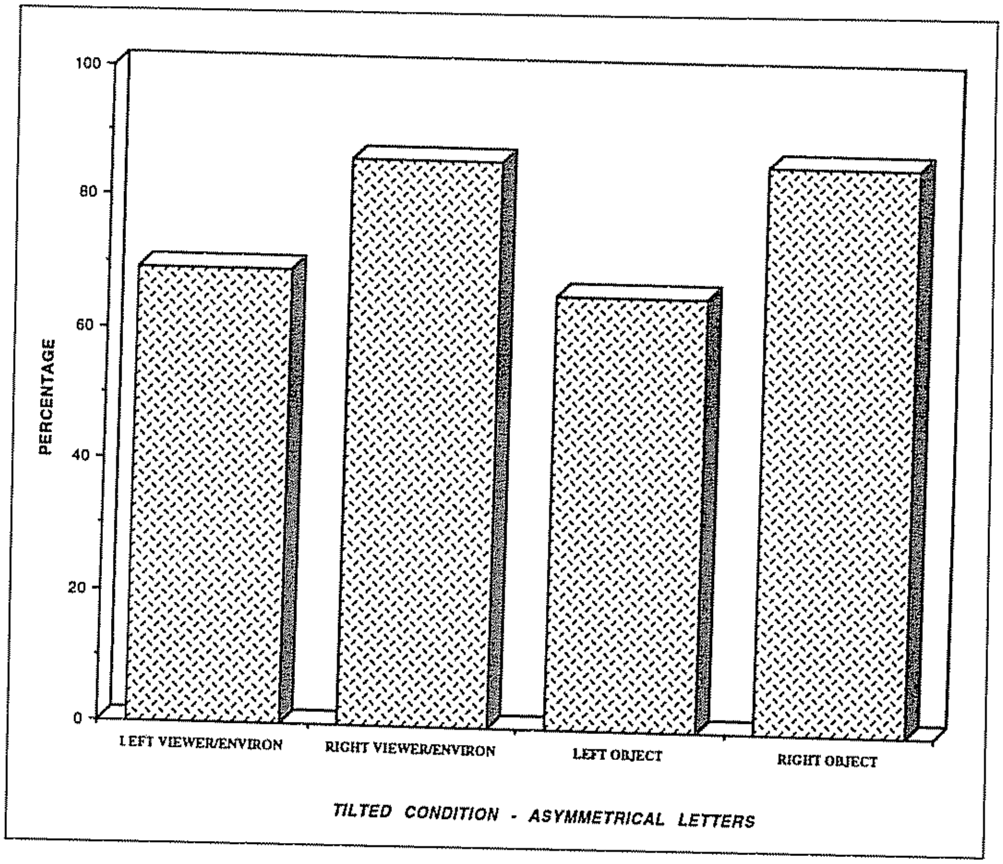


Figure 5. Mean percentage correct report of colors from left and right of asymmetrical letters defined in viewer/environmental coordinates (first two bars on the left) and in object coordinates (two bars on the right) in the tilted condition

line axis (Marr, 1982) is established, the left and right sides of the objects defined with respect to a frame centered on the object itself are marked Contralesional neglect then arises for information appearing to the left of this central axis

An alternative explanation, however, is that *all* letters, whether asymmetrical or not, can induce an object-centered neglect The prediction thus far is that it is the inherent asymmetry of the letters used in Experiment 2 rather than their status as letters that gives rise to the object-centered effect If this is indeed the case, then one might not expect to obtain a significant left–right difference, defined in object-centered coordinates, with symmetrical letters

EXPERIMENT 3: OBJECT-BASED NEGLECT IN SYMMETRICAL AND ASYMMETRICAL LETTERS

This experiment was identical to Experiment 2 except that, in addition to the asymmetrical letters used in Experiment 2, a set of symmetrical upper case block letters was added to the stimulus set The design of this final experiment was therefore a within-subject comparison contrasting the number of colors reported from symmetrical and asymmetrical letters in both the *upright* and *tilted* conditions

Results

With the symmetrical letters, subjects made a number of errors in identifying the letters, for example, calling the *I* (rotated 90°) a *T* and the *H* (rotated 90°) a *C* These errors, making up less than 5% of the trials, were excluded from the analysis The nature of these errors, however, is consistent with the previous finding that information on the left of the viewer and/or the environment is neglected by these patients Two subjects also made a single error each in the asymmetrical letters. Because trials on which the letter is misidentified are rejected, the number of trials differs for each subject Statistical t tests are thus conducted on the proportion correct report (following an arcsine transformation) The mean percentage colors across the six subjects reported from the left and the right of the symmetrical and asymmetrical letters in the *upright* condition is shown in Figure 6

In the *upright* condition, significantly fewer colors are reported from the left (quadrants 1 and 4) than from the right (quadrants 2 and 3) for both the asymmetrical and symmetrical letters, reflecting left-sided neglect for both types of stimuli [asymmetrical $t(5) = 5.18$, $p < 0.001$; symmetrical $t(5) = 8.1$, $p < 0.001$] The mean percentage correct report was 62 and 86% for the left and right of the asymmetrical letters and 60 and 89% for the left and right of symmetrical letters

Figure 7 illustrates the results of the *tilted* condition

Figure 6. Mean percentage correct report of colors from left and right of symmetrical and asymmetrical letters in the upright condition

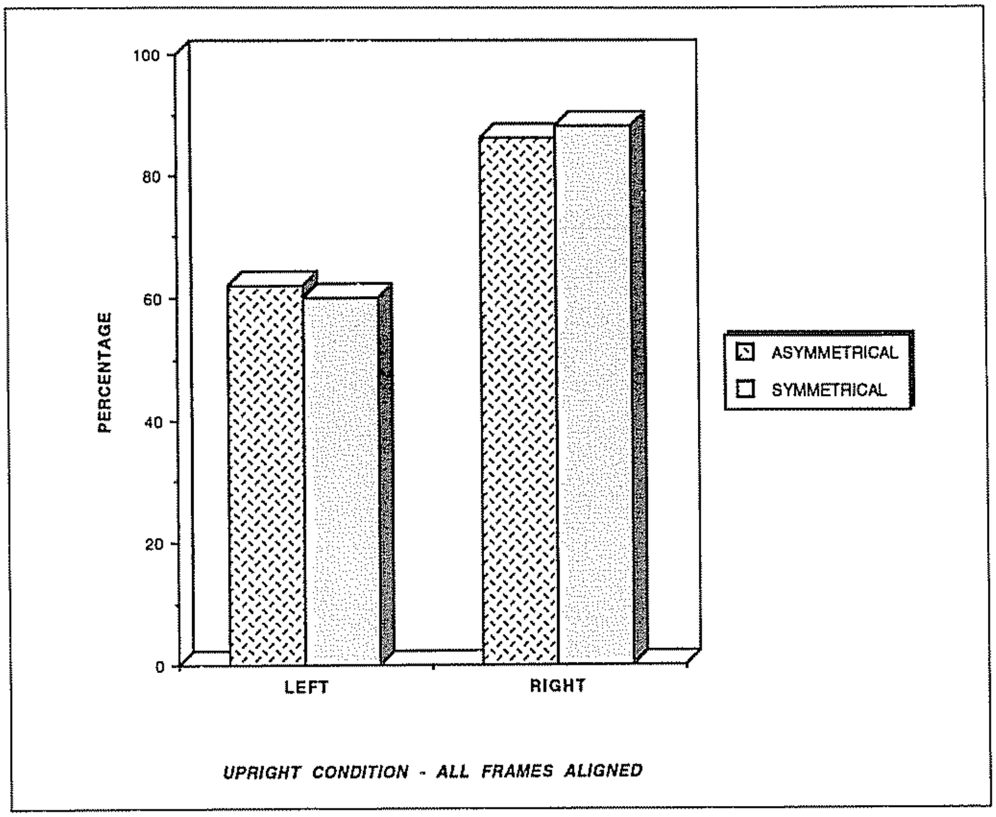
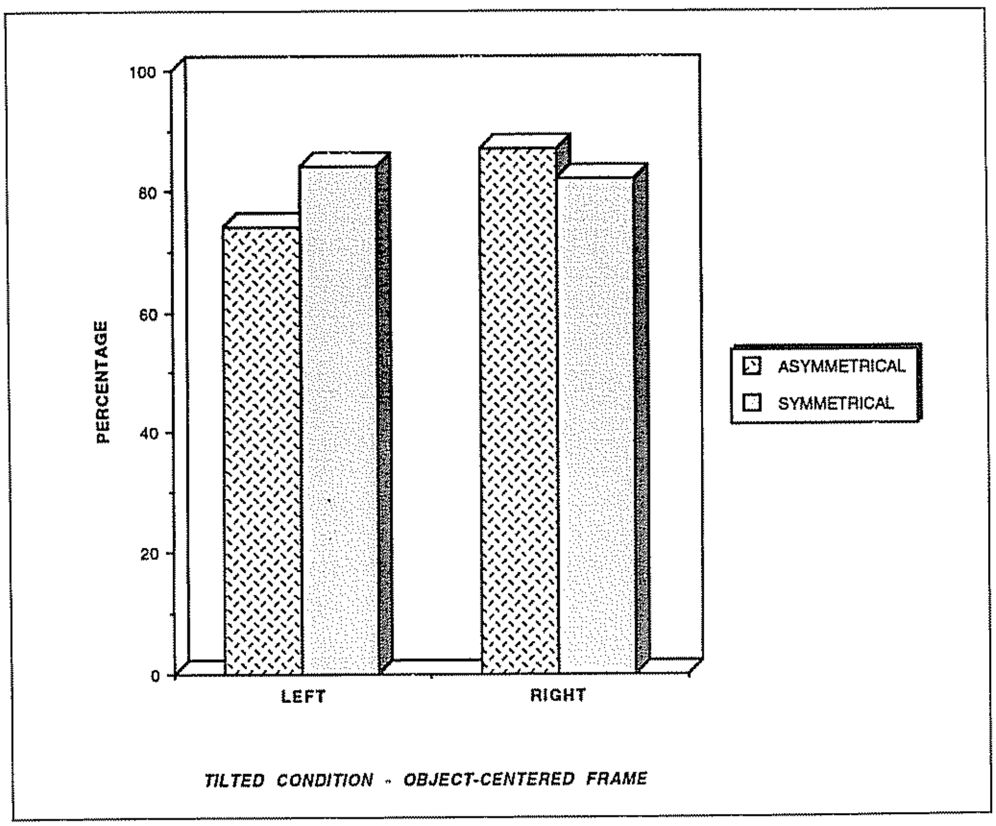


Figure 7. Mean percentage correct report of colors from left and right of asymmetrical and symmetrical letters defined in viewer/environmental coordinates in the tilted condition



and shows the mean percentage colors reported from the left (quadrants 1 and 4) and right (quadrants 2 and 3) of both letter types where left and right are defined by the viewer/env frame only. Here, colors appearing on the left of the asymmetrical letters (mean 73%) were reported significantly less often than colors appearing on the right (mean 89%) [$t(5) = 5.31, p < 0.005$]. Similarly, fewer colors were reported from the left (mean 74%) than from the right (mean 93%) of the symmetrical letters [$t(5) = 7.4, p < 0.001$], suggesting that neglect is defined with respect to viewer and/or environmental coordinates independent of stimulus type.

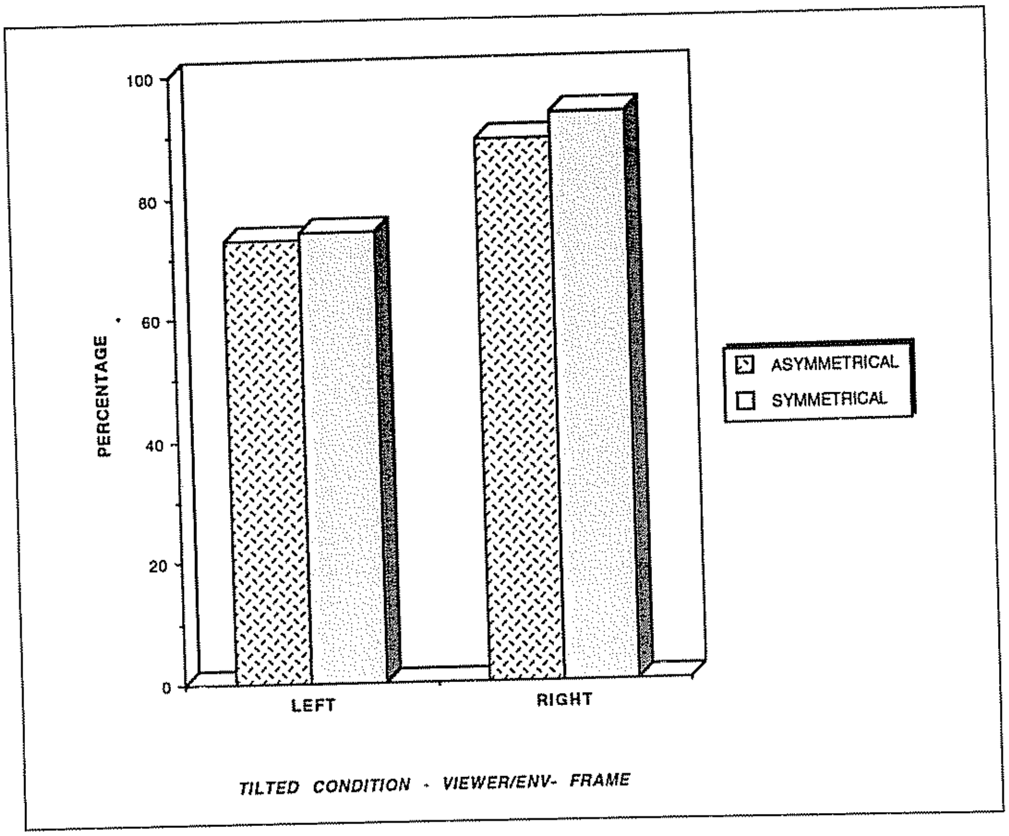
Figure 8 illustrates the percentage of colors reported from the left and right of both letter types where left and right now refer to the left and right of the object-centered frame. The results shown in Figure 8 demonstrate that when the comparison is made in object-centered coordinates, the results from the asymmetrical and symmetrical letters are not the same. There is now only a significant left–right difference on the asymmetrical letters [$t(5) = 2.64, p < 0.001$] but not on the symmetrical letters [$t(5)0.84, p = 0.44$]. Whereas 74 and 87% of the colors were reported from the left and right of the asymmetrical letters, respectively, 84 and 82% were reported from the left and right of the symmetrical letters, respectively. An examination of the individual scores of the patients shows that four of the six subjects reported fewer colors from the left of the asymmetrical letters than from the right while the remaining two subjects did not show the predicted object-based effect on any of the letters but also did not show the reverse effect. Importantly, of the four subjects who *did* show the effect on the asymmetrical letters, none showed the object-based effect on the symmetrical letters.

The two-way analysis of variance using viewer/env and object as within-subject variables was conducted on the data from the tilted and the tilted + upright condition separately for the asymmetrical and symmetrical letters as in the previous experiments. As in Experiment 2, with the asymmetrical letters, main effects of viewer/env and of object frame were observed both when the data were taken only from the tilted condition as well as when the data from the upright condition were included with the tilted data. The interaction between viewer/env and object frame [$F(1,5) = 62.3, p < 0.001$] was observed only in the tilted + upright analysis. On the symmetrical letters, on both analyses, only the main effect of viewer/env coordinates was significant [tilted $F(1,5) = 19.6, p < 0.05$; tilted + upright $F(1,5) = 18.8, p < 0.01$].

Discussion

The results of Experiment 3 are relatively straightforward. Overall, significantly fewer colors were reported from the left side than from the right side of both symmetrical and asymmetrical letters in the upright condition when all three frames of reference (viewer-, environment-, and object-centered) were aligned. This is consistent with the presence of contralesional hemispatial neglect. Significant left-sided neglect, defined in

Figure 8. Mean percentage correct report of colors from left and right of asymmetrical and symmetrical letters defined in object-centered coordinates in the tilted condition.



viewer/env coordinates, was also observed on both letter types when the stimuli were rotated 90° The most important finding, however, concerns the presence of left-sided neglect where left is defined in object-centered coordinates Significantly fewer colors were reported from the left of the asymmetrical letters than from the right when the object-based frame was decoupled from the viewer/env frame and there was a significant interaction between the viewer/env and the object frames of reference, a replication of the finding of the object-based effect demonstrated in Experiment 2 The same object-based neglect, however, was *not* observed with the symmetrical letters; there was no difference in the number of colors reported from the left and the right in an object-based frame of reference for these stimuli Even those subjects who showed the object-based effect on the asymmetrical letters failed to show the effect on the symmetrical letters These data suggest that object-based neglect does not arise for letters as a class; rather, the object-based effect is observed only on a subset of letters, those that are asymmetrical

GENERAL DISCUSSION

We have presented data from three experiments, all of which were designed to examine the spatial coordinates within which information is neglected by patients with right hemisphere damage The methodology involved measuring the number of colors reported from the left and the right of stimuli in two conditions: when the stimulus was presented upright or when it was rotated clockwise or counterclockwise These two conditions, *upright* and *tilted,* allowed us to measure separately the number of colors reported from the left and right defined with respect to a viewer/env-centered reference frame and with respect to an object-centered reference frame Three different sets of stimuli were used: drawings of familiar objects and animals (Experiment 1), asymmetrical letters (Experiments 2 and 3), and, finally, symmetrical and asymmetrical letters (Experiment 3) It was possible to demonstrate neglect for information on the left for all types of stimuli where left was defined in viewer and/or environmental coordinates The major finding of these studies, however, is that it was also possible to demonstrate neglect for the left where left was defined in object-centered coordinates This object-based effect, however, was specific to certain classes of stimuli: it was observed only for asymmetrical letters but not for symmetrical letters nor for familiar objects and animals

The finding that the subjects report information appearing on the left more poorly than information on the right where left and right are defined by viewer or environmental coordinates is consistent with the results of several previous studies (Calvanio et al , 1987; Farah et al , 1990; Young et al , 1992) The more interesting finding in the present set of studies is that under certain conditions, neglect may also be observed in coordinates defined by a frame of reference intrinsic to the object, consistent with results obtained in some (Behrmann & Tipper, 1994; Caramazza & Hillis, 1990a,b; Driver & Halligan, 1991; Young et al , 1992) but not all previous investigations (Farah et al , 1990) What remains to be explained is the specificity of the object-based effect

A possible determining factor that may account for the selectivity of object-based neglect may have to do with the handedness of the object Because the asymmetrical letters have a canonical handedness or intrinsic asymmetry, the left and right sides cannot be transposed if the identity is to be maintained Thus, the proper representation of the object relies critically on a central principal axis to mark and distinguish the two sides and to ensure that the left and right of the stimulus are not transposed Where there is no inherent left–right handedness, as in the case of symmetrical letters or in the drawings of familiar objects, it is not essential that the left and right be marked separately In these latter cases, left and right are determined solely by coordinates extrinsic to the object, i e , from a viewer or environmental perspective

The role of an object-centered reference frame in visual processing has a long history in the psychological literature The emphasis in that literature, however, has been on object identification rather than on spatially distributed attention to components of an already identified object, the question with which our study was concerned Nonetheless, we will describe briefly some of the recent results of these object-identification studies to provide a general perspective on the role of the object-centered frame in visual processing (for reviews of older literature see Corballis, 1988, Jolicoeur, 1985, and Rock, 1990) The primary method used in many of these recent studies that examine reference frames in object identification involves measuring the time it takes for subjects to identify or name an object as a function of its orientation The logic used in these experiments is that if intrinsic object-centered representations are being used in identification, then there should not be an effect of the orientation of the object on identification speed In contrast, if a reference frame other than an object-centered one is being used for identification, then reaction time should be affected by the object's orientation In one such study, Tarr and Pinker (1989, 1990) used a task in which normal subjects were required to identify abstract shapes presented at different orientations The findings demonstrated no reaction time difference as a function of orientation in the identification of symmetrical shapes, i e , identification time was independent of the orientation of the object In contrast, an effect of orientation was found with asymmetrical figures (both familiar and unfamiliar) such that recognition time was linearly related to the object's displacement from upright These findings were corroborated by McMullen and Farah (1991) who used naturalistic line drawings (like those used in Experiment 1 here) and found that effects of orientation appeared only for drawings of asymmetrical but not for symmetrical items (see also McMullen and Jolicoeur, 1990) Because stimulus orientation influences the identification of asymmetrical but not symmetrical objects, the conclusions from these studies are that object-centered representations are used for the identification of symmetrical but not asymmetrical stimuli (see also Corballis, 1988)

On the surface, the results of Tarr and Pinker (1989, 1990) and McMullen and Farah (1991), which suggest that symmetrical but not asymmetrical objects are coded in an object-centered frame of reference, appear inconsistent with our findings On closer examination, however, there are important and critical differences between those studies and ours Whereas these previous studies were interested in object identification as a function of orientation, our focus was different We took object identification for granted (even eliminating those trials in which there was misidentification) and were interested only in whether the distribution of attention is influenced by the boundaries of the object once the object has been identified It is possible, therefore, that in our study, in which the subjects were required to attend to and retrieve some perceptual information (color) from a correctly identified object, differential amounts of attention were deployed to the left and right sides where side is defined with reference to the object itself Thus, it may be the case that an object-centered reference frame is used differently for object identification and for distributing attention once identification has occurred.

A consistent finding of the studies on reference frames and attention has been that visuospatial attention can operate at multiple levels of visual information processing and that attention may be distributed in more than one reference frame (Humphreys & Riddoch, 1993; Kanwisher & Driver, 1992; Moscovitch & Behrmann, 1994; Tipper, Driver, & Weaver, 1991; Tipper et al , 1994) Accordingly, when attention is disrupted following brain injury, neglect may arise at a number of levels simultaneously (Caramazza & Hillis, 1990 a,b) The results of the present study support the finding of multiple levels of attentional distribution and show that if object-centered neglect is observed, it occurs along (and interactively) with neglect within other coordinate systems The cooccurrence of neglect in more than one frame of reference can be accommodated by theories of visual processing in a relatively straightforward manner During visual processing, the initial description of the visual image is represented relative to a frame of reference that is tied to the viewer's perspective (Marr, 1982) This level of representation provides the most concrete description of the external world At this stage, neglect operates in a viewer-centered frame of reference Following the initial viewer-centered coding, the object-centered representation is derived by redescribing the input relative to a more abstract frame centered on object axes Thus, in the course of processing a visual stimulus, there is a hierarchy of levels of representation, with each subsequent stage reflecting a progression of abstraction from the physical stimulus parameters to the canonical representation Although these stages may be computed in parallel (Hinton, 1981), the viewer-based frame is coded initially

When attention is distributed during the initial registration of the stimulus, less attention may be directed to the left than to the right, giving rise to neglect in the spatiotopic, viewer-centered frame Thus, during the early stages of processing where dimensions such as the size and color of the stimulus are encoded prior to identification, left neglect is defined within a viewer-centered frame (Behrmann, Moscovitch, Black, & Mozer, 1990; Mozer & Behrmann, 1990) Instances of this spatiotopic form of neglect are seen in the present study where the patients neglect information and report fewer colors on the left of the viewer-centered frame This is further illustrated by the finding that patients make errors in identifying the stimuli, calling an *H* rotated 90° clockwise a *C* It may still be the case that even at early stages of visual processing, asymmetrical and symmetrical images would be dealt with differently Driver, Baylis, and Rafal (1992), for example, showed that their patient with neglect was able to pick up the primitive symmetry information preattentively from the left of the display even though he was not able to make explicit symmetry judgments Once identification has occurred, the subjects can deploy attention to the identified object to determine the colors for report but now attention is deployed in an object-centered frame Our study indicates that during ongoing visual processing, the distribution of attention can be influenced simultaneously and interactively by more than one set of spatial coordinates (see also Tipper et al., 1994)

The account thus far, however, does not explain why the object-based neglect is seen only for asymmetrical letters One possible explanation is that in the case of the asymmetrical upper case letters, the right side, which is usually more informative (e g , *B, R, K*) attracts attention and exerts an abnormal hold on it (Kinsbourne, 1987; Ladavas et al , 1990) This explanation is consistent with the finding that adding information on the ipsilateral side can cause difficulty for patients in disengaging attention from that side in a visual search task (Eglin, Robertson, & Knight, 1989; also Kinsbourne, 1987) A related explanation is that the center of mass of the stimulus determines the distribution of attention For example, Grabowecky, Robertson, and Treisman (1993) showed that patients with neglect were less able to detect the presence of a contralateral target when an ipsilateral flank was present than when the display appeared without any flanks They argued that attention may be directed to the center of mass as the most probable source of information about salient features of the object, and because the center of mass was shifted rightward with the ipsilateral flank, increased neglect was observed This same argument could be applied to the asymmetrical letters in this study—because of the density of right-sided information and the relative paucity of features on the left, attention may be biased to the ipsilesional right side, giving rise to the neglect of the left of the object The effect of right-sided density, however, is observed even when the right side of the object does not occupy the right side of space Independent of the orientation, then, it is the canonical handedness of the letters that gives rise to the neglect of the object-centered left of asymmetrical objects A further finding of Grabowecky et al (1993) may help explain the results of the symmetrical letters and familiar objects In that study, when bilateral flanks were used, i.e , where perceptual information appeared on both sides of the central display that contained the target, targets on the contralateral side of the display were detected better than in the ipsilateral flank condition When salient perceptual information appears bilaterally, attention may be more evenly distributed across the entire object This seems particularly likely in the case where the object or letter has already been identified.

The primary deficit that is thought to give rise to the neglect phenomenon is that of a disruption of spatial processing such that visuospatial attention is not distributed evenly to the right and left sides Whereas there has been general agreement that right and left are defined by extrinsic coordinates, we have shown in this study that spatial coordinates defined intrinsic to the object can also influence the distribution of attention The deficit in viewer/env coordinates in hemispatial neglect found in the present study is consistent with the finding that most of these patients have lesions of the parietal lobe, the area responsible for coding spatial information (Stein, 1992) Our finding of object-centered neglect suggests that once the visual input is identified, the parietal lobe attention system may also operate on identified objects Exactly how this is accomplished is not known but one possibility is that the parietal lobe interacts with or is yoked to the ventral visual pathway that is involved in object identification (Humphreys & Riddoch, 1993; Horwitz, Grady, Haxby, Schapiro, & Rapoport, 1992; Ungerleider & Mishkin, 1982)

METHODS

Experiment 1

Subjects

Five right-handed, English-speaking subjects (one male, four female), undergoing rehabilitation following a right hemisphere stroke, consented to participate in this study The mean age of the subjects was 69 (range 58–77) and the number of weeks since onset ranged from 5 to 13 weeks All patients had CT-scan documented parietal lesions although the depth and extent of the lesion varied Subjects were screened for neglect using the Sunnybrook Battery for Neglect (Black, Vu, Martin, & Szalai, 1990), which includes tasks of drawing/copying, line bisection, figure cancellation, and line cancellation. Performance on this battery has been standardized on normal control subjects and points are assigned indicating the degree to which performance differs from the norm (e g , on line cancellation, 2 points is assigned for each omitted line) The five patients all had scores that exceeded the normal cutoff of 5 points The mean neglect index obtained by the subjects on the Sunnybrook Battery for Neglect was 34, indicating mild to moderate neglect

Materials

The stimuli consisted of 20 line drawings of real world objects (e g , a wishing well, a gorilla, a rabbit, a camel, a sailboat, a tree), selected from the Snodgrass and Vanderwart (1980) collection, and used by Farah et al (1990). The drawings, which were large enough to fill a sheet of 8 5 × 11 in paper, were presented individually to the patients The 10 drawings of animals were presented so that on half the trials, the animal faced left and on the remaining half, they faced right The outline or border of each figure was drawn in a series of colors Four different colors marked the outline of each quadrant, making a total of 16 different colors for the entire drawing (dark blue, light blue, black, dark green, light green, yellow, red, pink, orange, dark brown, light brown, mustard, light purple, dark purple, cerise, gray) No color appeared more than once in any drawing. Three versions of each drawing were constructed using a different ordering of the colors. Instead of requiring single letter report as in the Farah study, the subjects were required to report the different colors Prior to starting the experimental task, the subjects performed a color-naming task to ensure that they could differentiate and label the colors Color patches of the 16 colors used for the experiment were drawn on a single sheet and the subjects were required to name them individually Subjects were not required to use the words "mustard" or "cerise" necessarily; as long as they were able to consistently label the colors using whatever terms they preferred, they were judged to have passed the screening test. All subjects performed this color screening task without error.

Procedure

Subjects were tested at a table and the stimuli were presented on a music stand The subjects were required to name the object and to name the colors that formed the outline of the object The order of the object and color reporting was counterbalanced across subjects For all subjects except 1, the testing was completed in a single session The subjects viewed the stimuli under the two conditions shown in Figure 1a, *upright*—viewer and stimulus upright and Figure 1b, *tilted*—viewer upright, stimulus rotated 90° clockwise and counterclockwise Each subject viewed all 20 pictures under each condition The order of conditions was counterbalanced across subjects and a different version of each drawing was seen under different conditions Aside from this constraint, the order of the stimuli was random The subjects had an unlimited time in which to respond and the trial was terminated when the subject stated that she or he had named all the colors Although the subjects could potentially simply name all the colors without looking at the stimulus (as all 16 colors were used in all stimuli), they appear not to have done so and, more importantly, to have omitted to report more colors on the left than on the right as predicted

The number of colors reported correctly in each quadrant in each condition was calculated When the subject and the drawing were both upright (Fig 1a), all three reference frames coincided and the number of colors reported from the left (quadrants 1 and 4; maximum is 160) was compared with that from the right (quadrants 2 and 3; maximum 160) The critical comparison was the *tilted* condition in which the subject remained upright but the stimulus was rotated (Fig 1b) Since the viewer and environmental reference frames cannot be decoupled in this condition, they will be considered together (viewer/env) Under this condition, the number of colors from the left of the viewer/env-centered frame (maximum is 320 collapsed across the counterclockwise and clockwise rotations) was compared with that from the right (maximum is 320) The most important data come from the object-based frame and because the object-centered frame was decoupled from the viewer/env frame, an independent comparison could be made for colors reported from the left of the object (3 and 4 in counterclockwise and 1 and 2 in clockwise) with those from the right of the object

Experiment 2

Subjects

The same neglect and color screening tests described above were carried out on a new group of subjects Seven English-speaking subjects with neglect following a right cerebral infarction were included in this study The mean age of the subjects, five of whom were male, was 71 9 (range 59–82) and all subjects were right-handed Six of the subjects had sustained a middle cerebral artery infarction and had CT-scan-documented parietal lesions while the remaining subject had an aneurysm Five of the subjects were still undergoing rehabilitation (time since lesion onset ranged between 9 and 17 weeks), one subject was in a long-term care center (27 months post-onset), and one subject was at home (8 months post-onset) The mean severity score on the Sunnybrook Neglect Battery was 31 (mild to moderate neglect) with the range from 11 to 38

Materials

Ten upper-case letters of the alphabet which have a left-right asymmetry were selected These included *B, D, E, F, G, K, L, P, Q,* and *R* These letters were printed in block capitals at a size large enough to fill an 8 5 × 11 in page As in Experiment 1, the outline of the letters was drawn in color with 4 different colors appearing in each quadrant, resulting in a total of 16 colors Three versions of each letter were formed using different colors and yielding a total of 30 stimuli

Procedure

The method was identical to that of the previous experiment Because there was a limited number of asymmetrical letters, only 10 letters were seen in each condition rather than 20 objects as in Experiment 1 Subjects saw 10 letters upright and rotated 90° counterclockwise and clockwise The versions of the letter and conditions of viewing were counterbalanced across subjects The maximum number of colors to be reported in the upright condition is 160 (80 left and 80 right) while the maximum, collapsed across the two rotations, is 320 (160 left and 160 right)

Experiment 3

Subjects

Six subjects (four male) with right hemisphere damage who had not participated in any previous experiments took part in Experiment 3 The mean age of the subjects was 61 4 (one subject was 47 years old) All had sustained a middle cerebral artery infarct and had parietal lobe lesions on CT scanning The subjects all showed hemispatial neglect on the Sunnybrook Battery for Neglect and all completed the color screening test without error The mean neglect severity score was 27 (mild to moderate) with one subject showing mild neglect with a score of 9

Materials

In addition to the 10 asymmetrical letters, all subjects also performed the color report task on 10 symmetrical letters (*A, H, I, M, O, T, V, W, X, Y*) Three color versions of each symmetrical letter were constructed and used The asymmetrical letters used in Experiment 2 were also used here An equal number of asymmetrical (n = 10) and symmetrical letters (n = 10) were shown in both the *upright* and the *tilted* conditions and the number of colors reported from each quadrant was measured The version of the stimuli and the viewing conditions were counterbalanced across subjects As in Experiment 1, the maximum number of colors for report in the *upright* condition is 160 on each of the left and right and 320 from the left and 320 from the right in the *tilted* condition collapsed across the two rotations.

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