Shadows in the Brain

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Abstract

■ The aims of the present study were to investigate whether the processing of an object shadow occurs implicitly, that is without conscious awareness, and where physically within the human brain shadows are processed. Here we present neurological evidence, obtained from studies of brain-injured patients with visual neglect, that shadows are implicitly processed and that this processing may take place within the temporal lobe. Neglect patients with lesions that do not involve the right temporal lobe were still able to process shadows to optimize object shape perception. In contrast, shadow processing was not found to be as efficient in neglect patients with lesions that involve the right temporal lobe. ■

INTRODUCTION

Objects are not generally illuminated uniformly. Lighting under a particular set of conditions can produce shadows that may either help or hinder object recognition. We are often unaware of the sophistication of our perceptual ability to cope with different shadow conditions because object recognition is usually performed without effort. Thus, in everyday life, although we may be aware of the end product of our recognition, we may not be aware of the effect an object shadow may have upon recognition.

A variety of visual processing models exists that propose different ways in which shadows might affect object recognition. For example, image-based theories (of object recognition) suggest that the presence of shadows might play a role in the recognition/identification of an object (Gauthier & Tarr, 1997; Edelman & Bülthoff, 1992; Edelman, 1995; Poggio & Edelman, 1990). As suggested by Cavanagh (1991), the processing of an image involves a crude match of the image to a memory representation in which all image contours, including shadow contours, are used. In other words, once an object is selected, shadows are associated with that object. A possible problem with these models is that if shadows are encoded as part of an object's representation, their spurious luminance edges may be confused with the object's physical contours, thus impairing recognition. Other theories of object recognition, however, propose that the visual system discounts spurious features, such as shadows, and extracts only invariant features (e.g., object edges; Biederman & Ju, 1988; Marr & Nishihara, 1978). The implication here is that if shadows can be easily discounted they should not affect recognition.

Despite the interest in the role played by shadows in object recognition, not much research has been carried out to investigate how shadows affect the performance of object recognition tasks. Braje, Legge, and Kersten (2000) (see also Braje, Kersten, Tarr, & Troje, 1998) have explored the effects shadows have on the recognition of natural objects. For stimuli they used digitized photographs of fruits and vegetables, displayed either with or without shadows. In three experiments, the effects of shadow, color, and image resolution on naming latency and accuracy were evaluated. Performance was not found to be affected by the presence of shadows, even for grayscale, blurry images, where the shadows were difficult to identify. Although this study demonstrates that the recognition of objects such as fruits and vegetables is highly invariant to the complex luminance patterns caused by shadows, further investigation may be necessary to extend these findings to the recognition of other objects that can be encountered in the natural world.

In an attempt to investigate further the role played by shadows during the recognition of familiar objects other than fruits and vegetables, Castiello (2001) investigated whether recognition performance is sensitive to different features of both naturally cast and artificially attached shadows. Subjects were required to recognize familiar objects pertaining to various semantic categories (e.g., tools, geometric shapes) presented within their central field of vision, while the presence, position, and shape of the shadows were systematically manipulated. In line with previous visual search results where search efficiency slows down when objects in the visual scene have anomalous shadows (Rensink & Cavanagh, 1993), a general increase in response time was found when naming objects in incongruent shadow conditions, that

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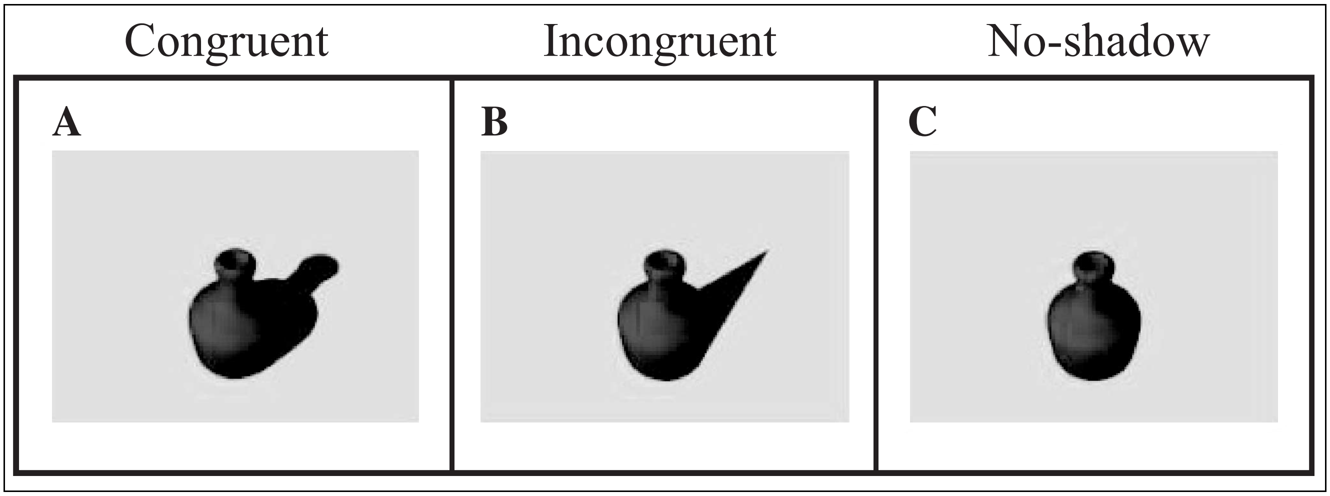

Figure 1. Examples of images used to depict the various object–shadow combinations. The shape of the shadows could be either congruent (A) or incongruent (B) with the shape of the objects. Shadows were presented to both the right and the left of the objects. Panel C depicts an object (a bottle) without a shadow. The objects depicted were: apple, banana, bottle, calculator, can, cross, cylinder, eraser, fork, glass, glove, jug, knife, mandarin orange, mug, pen, pyramid, sphere, tennis racket, and vase.

is, when the object was presented in conjunction with a shadow that originated from a different object.

Thus, overall, these studies indicate that humans can either marginalize the effect(s) shadows have such that object processing is invariant across different shadow conditions (e.g., Braje et al., 2000), or be affected by shadows in object recognition tasks when specific shadow manipulations are performed (e.g., Castiello, 2001). Nevertheless, in both cases these processes seem to be carried out without the explicit requirement of conscious awareness. In this respect, despite many studies of shadow perception suggesting that shadows are processed without any conscious awareness, direct evidence that this really is the case has not yet been provided. Thus, the first aim of the present study is to investigate to what extent the processing of shadows during an object recognition task occurs without conscious awareness. To this end, patients with visual neglect, who are particularly suitable when studying the relationship between visual processing and awareness, will be tested using object recognition tasks.

A further aim of the present study is concerned with determining the locus or loci of shadow processing within the human brain. The motivation behind this investigation is twofold. Firstly, no work currently exists that has investigated the possible anatomical basis of shadow processing during object recognition in humans. Secondly, this work might be of some relevance when considering the importance shadows have when performing tasks in which the correct perception of objects within an environment is fundamental to any subsequent requirement to navigate within the environment (Braje et al., 2000). For instance, cast shadows may be used to infer the height of an object above the ground (Yonas, Goldsmith, & Hallstrom, 1978), to provide information about 3-D shape (Cavanagh & Leclerc, 1989), and to disambiguate convex from concave surfaces in shaded images (Erens, Kappers, & Koenderink, 1993). Thus, localizing a pool of areas involved in this processing may allow us to better understand both the nature of the mechanisms underlying the ability to recognize objects under different illumination conditions, and the residual mechanisms that allow patients with lesions in areas that may be critical for object recognition to preserve some ability to interact with the environment. To this end, in the second study reported here we have used the brain localization approach to understand whether there is some evidence in the human brain for areas where shadows are processed.

STUDY 1: AWARENESS OF SHADOWS AND THEIR PROCESSING

The first study was designed to examine the link between conscious awareness of shadows and their processing during an object recognition task. A crucial test might be provided by studying the fate of those stimuli that escape awareness in patients with discrete brain lesions (Mattingley, Davis, & Driver, 1997; Làdavas, Paladini, & Cubelli, 1993; Berti & Rizzolatti, 1992; Driver, Baylis, & Rafal, 1992; Marshall & Halligan, 1988). Here we focus on the neurological phenomenon of ‘‘neglect,’’ which is observed after the occurrence of lesions in various regions of the brain, but especially those involving the right parietal lobe (Bisiach & Vallar, 1988). Visual neglect refers to the defective ability of patients with unilateral brain damage to attend to the side of space contralateral to the lesion (contralesional), and to report stimuli presented in that portion of space. Nevertheless, in some cases neglected information can be processed implicitly. For instance, a number of studies indicate that attributes of neglected stimuli still are encoded by the neglect patient's visual system despite the loss of awareness (Mattingley et al., 1997; Làdavas et al., 1993; Berti & Rizzolatti, 1992; Driver et al., 1992; Driver, 1996; Marshall & Halligan, 1988). In other words, it is possible to reveal the influence of neglected information without requiring the patient to report explicitly what the effective information is, which is typically precluded by their neglect.

A prediction arising from the notion of preserved implicit processing in neglect is that shadow processing should proceed normally on the contralesional left side with impairment arising only at some later stage. To test this prediction we compared a group of (six) patients with "left-sided visual neglect" (neglect) to a group of (six) patients with "right-hemisphere stroke without neglect" (RWN) and a group of (six) "neurologically healthy subjects" (controls). We used a protocol (Castiello, 2001) that allowed us to measure the time taken to recognize objects presented (individually) with either their naturally cast shadows ("congruent"), with shadows that originated from different objects ("incongruent"), or without a shadow ("no shadow"; see Figure 1A, B, and C, respectively). Shadows were presented to both the right and the left of the objects.

Results and Discussion

An analysis of variance (ANOVA) with group (neglect, RWN, controls) as a between-subjects factor, type of shadow (congruent, incongruent, no shadow) and side of shadow (right, left) as a within-subjects factor was performed. The quantity of errors was found to be negligible and therefore has not been analyzed. The main factor group was significant, $F(2,5) = 46.22$, $p < .0001$. The mean reaction time (RT) calculated for the neglect group was longer than both the mean RTs for the RWN group and the control subjects (1203, 1062, and 778 msec, respectively). The main factor type of shadow was also significant, $F(2,10) = 31.27$, $p < .001$. The mean RT for the objects presented with incongruent shadows was greater than the mean RT for the objects presented with congruent shadows (1111 vs. 929 msec, respectively). Objects presented without shadows gave intermediate values (mean, 1003 msec). The main factor side of shadow was not significant, $F(1,5) = .54$, $p > .05$. The mean RTs were 1017 and 1013 msec for the objects presented with left and right shadows, respectively. Furthermore, the main factor side of shadow did not interact significantly with the main factors group and type of shadow. The performance of the six control subjects is shown in Figure 2A. When asked to identify the object, identification speed varied according to the relationship between the shape of the object and the shape of the shadow. The response pattern of the six RWN patients was not different from that of the healthy volunteers who had not suffered a stroke, despite a generalized slowness in response (Figure 2B). When the six patients with neglect were asked to perform the object identification task, their performance was similar to the performance of the other two groups despite a generalized increase in response time, showing an influence of the rejected left shadow. They were faster to identify the object when presented with its naturally cast (i.e., congruent) left shadow than with an incongruent left shadow (Figure 2C). In the no-shadow condition, neglect patients showed intermediate values. This did not differ significantly from the performance of the RWN patients. All in all, the three groups showed a similar pattern with respect to the processing of shadows.

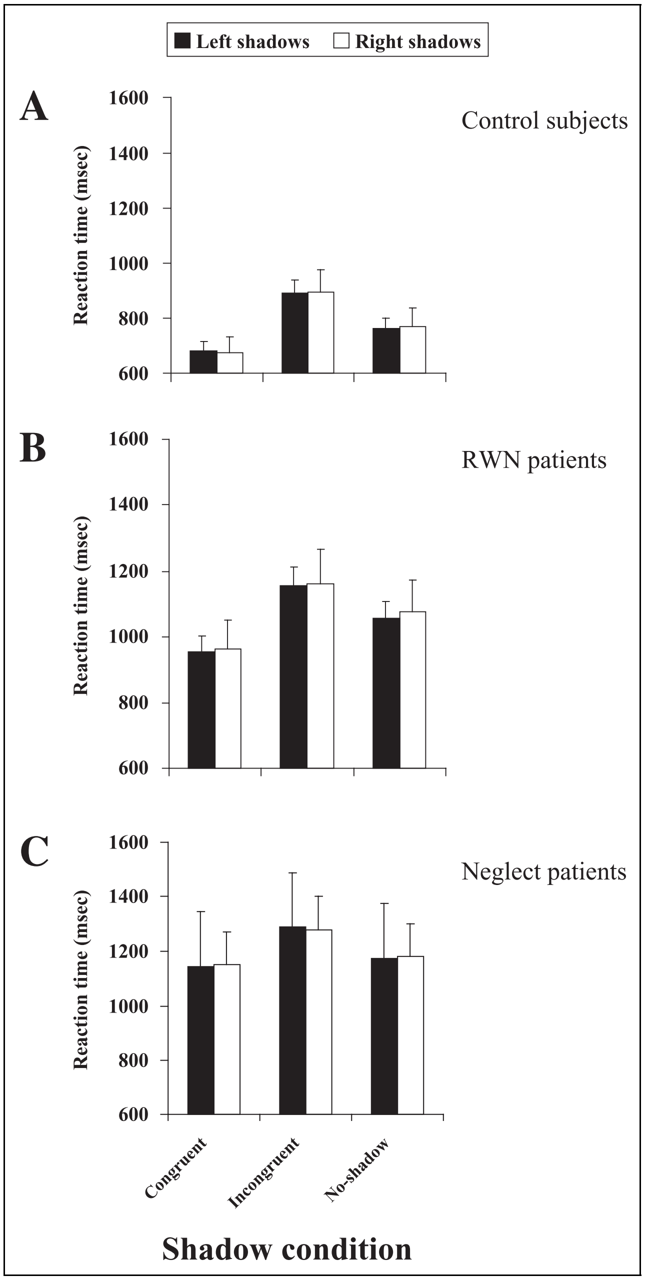

Figure 2. A graphical representation of the nonsignificant interaction among group, side of shadows, and type of shadow for Study 1. The error bars correspond to the standard errors of the means.

Results from a forced-choice test (please refer to the Methods section) revealed that patients with neglect were severely impaired when the shadows were presented to the left of the objects. For 92% of trials they denied the presence of the left shadows compared with 2% for the right shadows ($p < .0001$).

These results support the ''implicit'' prediction, demonstrating that the critical variable was the implicit integration of the shadow into the description of the target object. This implies that, like normal observers, neglect patients can process a shadow for object-shape information, irrespective of whether it appeared on the right or the left of the object (Figure 2A–C). Thus, the patient's left neglect arises at a stage subsequent to the stage where luminance patterns caused by shadows are processed to yield object shape information. In this respect, we have shown that the neglect patients who took part in the present study can still use the information from left shadows, even though they do not consciously perceive them, to recognize objects.

STUDY 2: WHERE WITHIN THE HUMAN BRAIN IS SHADOW INFORMATION PROCESSED?

Now we turn to the second question addressed in the present study, that is, where physically within the human brain shadow information is processed. As a starting point we relied on some evidence of shadow and illumination invariant processing obtained from lesion studies and cellular recordings in monkeys. These studies suggest that cells responding to shadows are buried within the superior temporal sulcus (STS; Hietanen, Perrett, Oram, Benson, & Dittrich, 1992; Perrett, Mistlin, & Chitty, 1987), and that other high-level object processing ventral areas, such as the inferotemporal cortex (IT), are critical for object recognition under varying conditions of illumination (Vogels & Biederman, 2002; Weiskrantz & Saunders, 1984). Despite the difficulties involved in making homologies between monkey and human brain areas, recent human studies conducted with event-related potentials, positron emission tomography, and functional magnetic resonance imaging have identified a possible homologue for these temporal areas in humans (Allison, Puce, & McCarthy, 2000; Hoffman & Haxby, 2000). Therefore, assuming that lesions within the human temporal lobe also produce a deficit in human shadow processing ability, patients with neglect as a consequence of lesions involving segments of the temporal lobe will be unable to process implicitly shadows as efficiently as patients with neglect derived from lesions not involving the temporal areas. We tested this prediction by assessing the performance of an additional group of neglect patients with temporal lesions (''temporal'' group; Table 1). Their performance was compared with the performance of four neglect patients with lesions not involving the temporal cortex, but the frontal cortex (''frontal'' group; Table 1), a group of RWN patients (Table 1), and a group of control subjects. The protocol used was the same as for the first study.

Results and Discussion

An ANOVA with group (frontal, temporal, RWN, controls) as a between-subjects factor, type of shadow (congruent, incongruent, no shadow), and side of shadow (right, left) as a within-subjects factor was performed. The quantity of errors was found to be negligible and has therefore not been analyzed. The main factor group was significant, $F(3,3) = 22.11$, $p < .0001$. The mean RTs calculated for the patients in the frontal group (1215 msec), the temporal group (1298 msec), and the RWN group (1080 msec) were larger than the mean RT for the control subjects (776 msec). The mean RT for the RWN group was significantly smaller than both the mean RTs for the frontal and the temporal groups. No significant differences were found between the frontal and the temporal groups. The main factor type of shadow was also significant, $F(2,6) = 14.22$, $p < .001$. The mean RT for the objects presented with incongruent shadows was greater than the mean RT for the objects presented with congruent shadows (1177 vs. 1029 msec, respectively). Objects presented without shadows gave intermediate values (mean, 1070 msec). The main factor side of shadow was not significant, $F(1,3) = 1.03$, $p > .05$. The mean RTs were 1090 and 1095 msec for the objects presented with left and right shadows, respectively.

The interaction among group, type of shadow, and side of shadow was found to be significant, $F(3,3) = 21.07$, $p < .001$. Post hoc comparisons revealed that when the four patients with neglect that comprised the frontal group were asked to perform the object identification task their performance was similar, despite an increase in response time, to the performance of both the control subjects and the RWN group, signifying the influence of the rejected left shadow. As found for both the four control subjects (Figure 3A) and the four RWN patients (Figure 3B) they were faster to identify the object when presented with its naturally cast (i.e., congruent) shadow than with an incongruent shadow, irrespective of the position of the shadow with respect to the object (Figure 3C). In the no-shadow condition, these patients showed intermediate values, as did the other two groups (Figure 3A–C).

In contrast to the control subjects, the RWN patients and the patients with left-sided visual neglect following frontal lesions, the four patients with left-sided visual neglect following temporal lesions showed a different pattern of performance during object identification. They showed similar results to the other groups when the shadows were presented to the right of the objects (Figure 3D), but they were slower to identify the objects when presented in conjunction with shadows to the

Table 1. Demographic and Clinical Data for the Neglect Patients

Patient No.	*Age*	*Sex*	*Lesion*	*Visual Field*	*Post Stroke (Days)*	*Clinical Tests* *Line Bisection Test (mm)*	 *Albert's Line Test (/36)*	 *Star Cancellation Test (/54)*
Neglect patients (Study 1)								
1[a]	67	F	FP	Normal	56	12.2	15	13
2[a]	75	M	FPO	Normal	60	7.8	23	20
3[a]	69	F	FP	Normal	64	17.3	34	24
4[a]	71	M	FP	Normal	58	21.2	26	14
5	74	F	P	IQ	57	12.3	22	7
6	75	M	BG	SQ	66	11.6	33	27
Mean						13.73	25.5	17.5
Neglect patients (Study 2) temporal group								
1	69	F	TPO	LIQ	65	11.1	13	10
2	77	F	TP	Normal	59	10.8	22	8
3	70	F	TP	Normal	55	13.4	36	20
4	73	M	TP	Normal	61	18.7	32	13
Mean						13.5	25.7	12.7
Right lesion—without neglect patients (RWN) (Study 2)								
1[a]	73	M	P	Normal	64	0.1	36	54
2[a]	77	F	P	Normal	67	0.5	36	53
3[a]	75	F	BG	Normal	58	1.0	36	52
4[a]	69	M	BG	Normal	63	0.4	36	54
5	75	F	F	Normal	59	2.0	36	54
6	77	M	F	Normal	60	1.0	36	54
Mean						0.8	36	53.5

IQ = inferior quadrantanopia; SQ = superior quadrantanopia; LIQ = lower inferior quadrantanopia; F = frontal; P = parietal; O = occipital; BG = basal ganglia.

[a]Patients who took part in both studies.

left, independently from whether the shadow was congruent or incongruent (Figure 3D). In the no-shadow condition, the neglect patients of the temporal group showed lower values than for the shadow conditions (Figure 3D).

With respect to the forced-choice test when the patients in the frontal group were required to report the presence of the shadows verbally, they were severely impaired when the shadows were presented to the left of the objects. For 98% of trials they denied the presence of the left shadows compared with 2% for the right shadows ($p < .0001$). When the patients in the temporal group were required to report verbally the presence of shadows in this forced-choice test, similar to the frontal group they were severely impaired when the shadows were presented to the left of the objects. For 95% of trials they denied the presence of the left shadows compared with 1% for the right shadows ($p < .0001$). In this respect, we have demonstrated that the neglect patients with lesions involving the right temporal lobe who took part in the present study cannot use the information from shadows positioned to the left of objects to optimize object recognition. Furthermore, this study shows that when the shadows are not presented, their performance improves significantly (Figure 3D).

These results support in part the temporal prediction, demonstrating that the integration of the shadows into the description of the target objects may occur within the temporal areas of the right hemisphere. This implies that unlike the subjects in the other groups, neglect patients belonging to the temporal group could not use shadows for recognition when they appeared to the left of the objects.

GENERAL DISCUSSION

We have presented data from two studies designed to examine the nature of shadow processing. The methodology involved object recognition in three conditions: when the object was presented with a congruent shadow (to the right or the left), when the object was presented with an incongruent shadow (to the right or the left), and when the object was presented without a shadow. These three conditions allowed us to measure the point at which the visual processing of shadows is taken into account during object recognition, and which brain areas are responsible for this processing. It was possible to demonstrate neglect for shadow information on the left for all objects. The major findings of these studies, however, are that it was possible to demonstrate that shadow processing in humans is outside conscious awareness, and with a certain degree of caution, that this processing occurs within temporal areas that may be the homologue of the monkeys' temporal areas where shadow processing occurs.

The finding that the neglect patients were unable to report shadow information even though they were able to process it is in accordance with a previously described dissociation between implicit processing and verbal report in visual neglect (Mattingley et al., 1997; Driver et al., 1992; Driver, 1996; Marshall & Halligan, 1988). Behavioral studies have shown that residual unconscious processing of the information neglected by the patient can still take place (Pouget & Driver, 2000; Driver, 1996). For example, a patient's response time can be influenced not only by the presence of the neglected visual stimulus, but also by a number of features such as color, shape, identity, and semantics. In accordance with these previous findings, our results show that shadows can be processed implicitly as it has been demonstrated for other object attributes. However, the nature of our task and the differences in the results obtained for the frontal and the temporal groups of neglect patients allow speculation regarding the brain areas concerned with unconscious processing, at least for the unconscious processing relative to shadows.

A compelling hypothesis proposed by Driver and Vuilleumier (2001) to explain unconscious behavioral

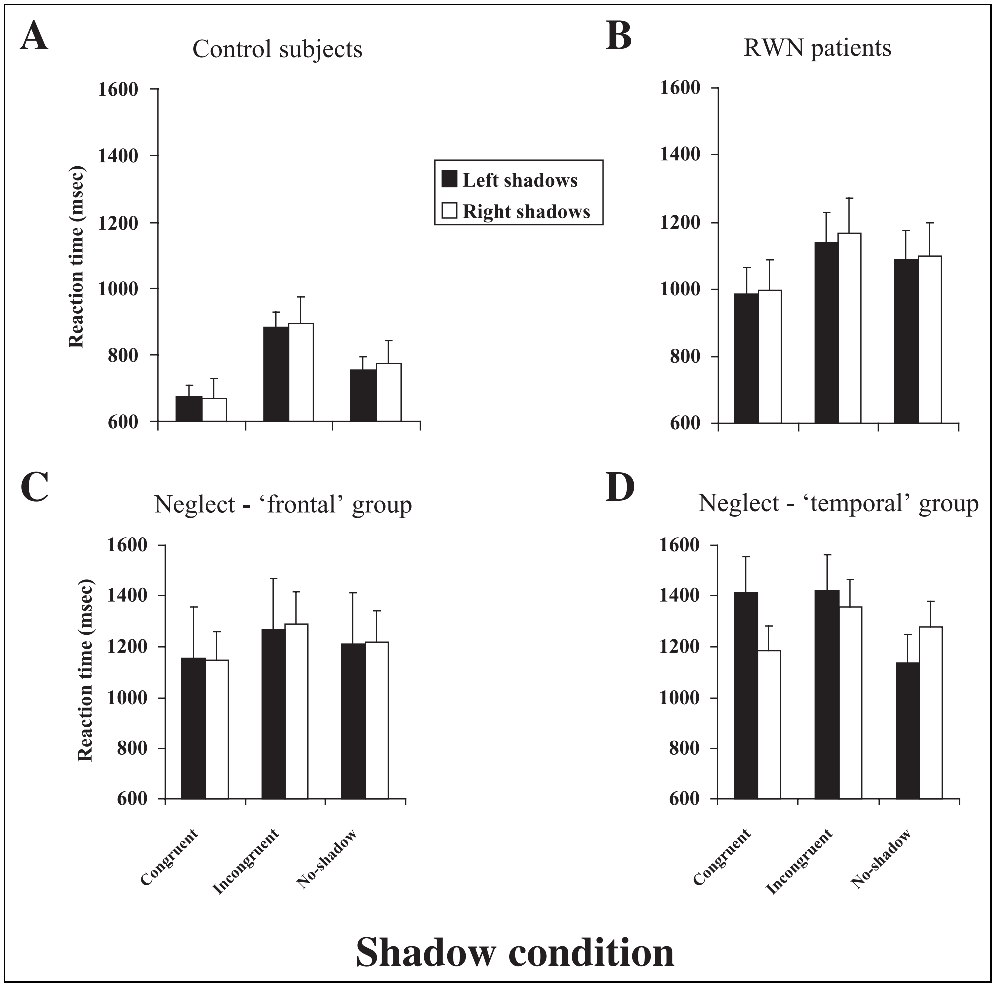

Figure 3. A graphical representation of the significant interaction among group, side of shadows, and type of shadows for Study 2. The error bars correspond to the standard errors of the means.

processing states that this processing occurs not only within early visual areas of the occipital lobe, but also along the ventral pathway into the temporal lobe. To date, patients with neglect typically suffer lesions that can leave posterior occipital and inferior temporal lobe cortices relatively intact. Consequently, it could be hypothesized that these brain areas may still receive input from contralesional stimuli to support the unconscious activation of representations for identity and semantics. In the present study, the role proposed for the residual temporal areas, which allows the unconscious processing of visual information in humans with visual neglect, seems to be supported. In particular, if undamaged temporal areas provide the substrate for preserved implicit processing, the present study confirms that while unconscious shadow processing remains possible when shadows are projected to the right, it becomes less possible when shadows are projected to the left, thus implying that the residual right temporal areas of the frontal group may still allow unconscious processing to take place, while the damaged right temporal areas of the temporal group do not allow unconscious processing to take place.

The possibility that temporal lesions might affect shadow processing and illumination-invariant object recognition comes from observation of the consequences of experimental lesions in monkeys (Vogels & Biederman, 2002; Hietanen et al., 1992; Weiskrantz & Saunders, 1984). The focus found here in the patients with right temporal lesions conceivably suggests, from both the behavioral and the anatomical perspective, that the temporal cortex may be the substrate of shadow processing in humans. However, (in this study) it must be noted that the lesions measured for the temporal group patients are very extensive and span throughout the entire ventral visual areas. So claims of localizing the exact areas responsible for the processing of shadows need to be treated with great caution. Nevertheless, the fact that patients with temporal lesions show a dissociation between conscious awareness of shadows and their processing, together with an improved performance when shadows are not present, points towards a possible role played by these areas for the coding of shadows and their processing.

Given the extent of the lesions involving large portions of the ventral object recognition stream for the temporal group, a further issue that needs some discussion is concerned with the possibility that patients in the temporal group might experience problems when required to recognize objects presented centrally. Despite the neglect patients showing no evidence of dysfunctional object recognition processes when the object is presented centrally, in some cases, however, object-centered neglect has been found (e.g., Behrmann & Moscovitch, 1994). For example, patients show difficulties in the identification of chimerical figures where the left part of the figure is different from the right side, such that the right side alone is not sufficient to identify the entire object. So, it may be advanced that some patients in this study may have some problems in identifying central objects and, consequently, the lack of congruent/incongruent effects when the shadow is presented in the left visual field might be due to their inability to appropriately recognize the left part of the object and to match it with the shape of the shadow. Although we did not specifically test for object-centered neglect, before the experimental sessions commenced we conducted an object familiarity test to ensure that all of the subjects were able to effortlessly recognize the objects when they were presented within their central vision. All subjects who took part in this study were able to recognize the objects and to report their names.

Two final issues are concerned with the nature of the stimuli utilized. Firstly, it may be possible that the shadows in the displays were not necessarily treated as shadows. For example, the symmetry relations in the boundary contours of the stimuli are very different between the congruent and incongruent images. Likewise, the boundary contour features presented by the congruent case are all valid for the to-be-recognized objects, whereas in the incongruent case the boundary contours are incorrect. Thus, it might be possible that the similarity between object and shadow in the congruent case would improve detection times, whereas in the incongruent case there would be masking due to dissimilarities. However, one line of evidence may counteract this possible confound. That is, during the forced-choice test, where all the visual stimuli were presented and the subjects were asked to report whether the image included a shadow (or not), the subjects reported the presence of both congruent and incongruent shadows without posing any questions that led the experimenter to doubt that the incongruent shadows were not perceived as shadows. Secondly, the type of shadows utilized in the present study provide ‘‘structural’’ information regarding the objects—that is, the shape of the shadows is related directly to the shape of the object. As such, the role that shadows play here (and how they may or may not be interpreted/discounted) might be very different from shadows cast on the surface of an object, but providing no structural information. So to some extent, under present conditions, the question that remains and that needs further investigation is whether what is reported here is confined solely to silhouette interpretation (Tarr, Kersten, & Bülthoff, 1998; Kersten, Knill, Mamassian, & Bülthoff, 1996; Kersten, Mamassian, & Knill, 1997).

In conclusion, whatever the exact mechanism(s) responsible for the normal processing of shadows in neglect patients, the results presented here show that it is not only the presence of a shadow that matters, but also its particular shape, even for the patients who are completely unaware of it, and furthermore, that this link between object and shadow shape may occur within the temporal lobe.

METHODS

Study 1

Subjects

Six patients with left-sided visual neglect following right-hemisphere stroke were assessed, in addition to six RWN patients and six control subjects. The right-hemisphere patients were classified either as neglecting or not neglecting on the basis of neurological assessment, behavioral observation, and standard clinical tests (see Table 1) such as the line bisection test, the Albert's line cancellation test (Albert, 1973), and the star cancellation from the Behavioural Inattention Test (Wilson, Cockburn, & Halligan, 1987). The two cancellation tasks revealed that neglect patients always detected more targets on the right side than on the left. All patients had their lesions confirmed by CT scan. Their lesions were plotted (Figure 4) using the templates of Damasio and Damasio (1989). The patients in the RWN group had suffered cerebrovascular accidents involving various cortical and subcortical regions: two of the basal ganglia, two of the frontal lobe, and two of the superior parietal lobe. The six patients in the neglect group had suffered frontal infarcts, with the region of greatest lesion overlap in the inferior frontal lobe (Figure 4A). This region has been found to be the critical lateral frontal area associated with neglect (Husain & Kennard, 1996). One subject had suffered a parietal stroke largely involving the inferior parietal lobe (Figure 4B), the cortical area most commonly associated with neglect (Vallar & Perani, 1986). One subject had suffered a hemorrhage of the basal ganglia. Patients were excluded from the study if they had dementia and/or suffered from a previous neurological illness. Patients were also excluded if they showed severe gaze palsy.

One-way ANOVAs revealed that there was no significant (*ns*) difference among the mean ages [neglect patients: 72 years; RWN: 74 years; controls: 73 years; $F(2,15) < 1$ *ns*], the mean lesion volumes [neglect

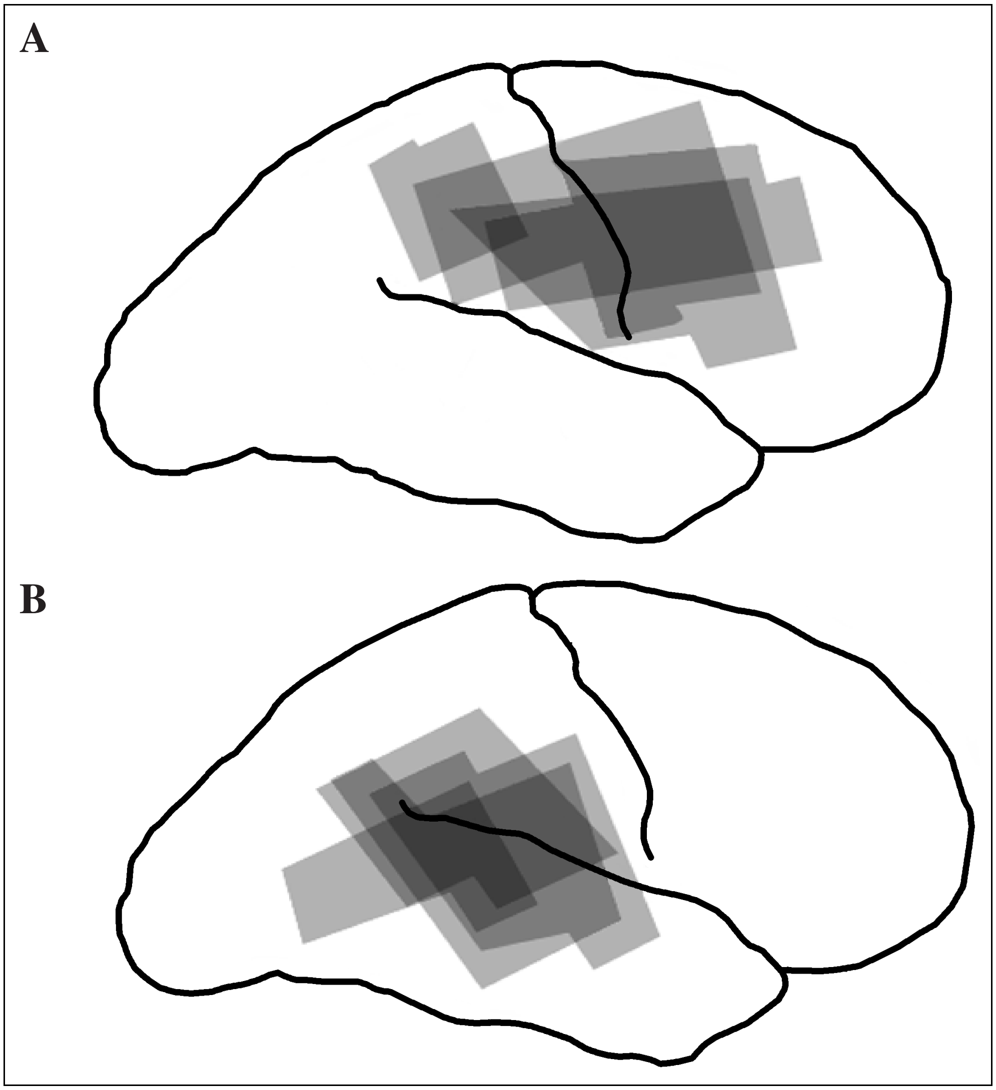

Figure 4. A depiction of the sites of the cortical lesions identified from CT scans for (A) five (out of six) of the patients with visual neglect but no temporal lesions (the lesions of the patient with subcortical damage are not represented), and (B) the four patients with visual neglect for the temporal group. In both examples the darker areas denote the regions of lesion overlap. The two lesion foci were in the inferior frontal lobe and the superior temporal gyrus, respectively.

patients: 41 cm^3; RWN: 39 cm^3; $F(2,10) < 1$ *ns*], and the mean days after stroke [neglect patients: 60; RWN: 61; $F(2,10) < 1$ *ns*]. All subjects gave informed written consent before testing began. The study was approved by the ethics committee of the North Western Health Care Network.

Materials

The stimuli used for these experiments were 20 (familiar, everyday) objects (chosen for their strong geometrical shape properties; for an example, see Figure 1; for the entire list of objects used, see Figure 1 legend) synthesized using the 3-D rendering package POVRAY. When generating these digital images the objects were positioned at the origin of an imaginary set of (x, y, z) axes, with y pointing orthogonally out of the image (i.e., towards the subjects), and x and z the horizontal and vertical axes, respectively. The camera was positioned along the y-axis such that it looked down upon the objects at an angle of 45°. The objects were illuminated with ambient and point light sources either from the right or from the left in order to avoid the effects of up/down illumination changes on perceived shape. The right and left light sources were located at ±34° along the x–y plane, respectively, again pointing down upon the objects at an angle of 45°. The reflectance model used an ambient reflectance of 0.2. The shadows without objects were generated by moving the objects towards the light sources, out of the camera's field of view. The objects were then scaled so that these (generated) shadows were in proportion to the original objects. These shadow and object images were then digitally combined to create the final image. All subjects viewed the objects binocularly from a distance of approximately 70 cm. The area subtended by the objects, including the shadows, was 7.8° × 7.8° of visual angle. The following experimental conditions were tested: (i) one of the 20 objects presented with its naturally cast shadow (congruent; Figure 1A); (ii) 1 of the 20 objects presented with a shadow representing 1 of the other 19 objects (incongruent; Figure 1B); (iii) 1 of the 20 objects presented without a shadow (no shadow; Figure 1C). Please note that in the no-shadow condition the objects were still presented with some lighting on the right or on the left. In order to take this factor into account, the no-shadow condition was analyzed in terms of right and left shadows. All the conditions were implemented during a single session and in counterbalanced order to rule out any influences of practice or long-term recovery on the comparison of interest. The order of every trial's presentation sequence was randomized across subjects.

Procedure

Subjects sat and were asked to look at the computer screen for the entire length of each trial, having been instructed to wait for the appearance of the objects (with or without any shadow, depending on the condition) in the center of the screen. The experiment was conducted in two parts. In the first part of the experiment the subjects, when ready, initiated a trial by depressing a computer mouse button. They were then required to report as quickly as possible the identity of the presented object. The vocal RT was taken from the time at which the stimulus first appeared to the time at which the subject emitted an audible vocal response, detected by means of a voice key. The end of the trial was taken as either the time of the vocal response or 2000 msec after the stimulus presentation if no response was made. The subsequent trial was presented after an interval of 2000 msec. Each participant first completed 20 practice trials, which were followed by four blocks of 100 trials. The duration of each block was no longer than 20 min and all blocks were separated by a rest period of 5–10 min. Trials in which errors of anticipation (i.e., RTs of less than 150 msec) occurred, no response was made, or the responses were made after 2000 msec had elapsed were automatically reset to the end of the block to be re-presented in a random order. Catch trials, where no object appeared, were also included in order to prevent expectancy and/or practice effects.

In a separate session, the visual stimuli were presented and subjects were asked to report whether the image included a shadow. This experiment was identical to the first except that the subjects were required to report verbally the presence of the shadow at the end of each trial. No RT was measured. This second experimental session was always run after the first had been completed.

Study 2

Subjects

Four additional patients with left-sided visual neglect who had lesions centered on the right temporo-parietal junction (temporal group; Figure 4B) were tested. Three patients had suffered temporo-parieto infarcts and one subject had suffered a temporo-parieto-occipital infarct (see Table 1). Earlier work has determined that these regions are associated with neglect in humans and monkeys (Karnath, Ferber, & Himmelbach, 2001; Watson, Day, Valenstein, & Heilman, 1994). These patients were compared with four stroke patients (the frontal group) with right-hemisphere fronto-parietal lesions (that did not involve the temporal lobe) and left unilateral neglect, four right-hemisphere patients without clinical neglect (RWN), and four control subjects. Some members of the latter three groups had also taken part in Study 1 (see patients marked with asterisks in Table 1).

One-way ANOVAs revealed that there was no significant difference among the mean ages [neglect frontal group: 71 years; neglect temporal group: 72 years; RWN: 73 years; controls: 72 years; $F(3,3) < 1$ *ns*], the mean lesion volumes [neglect frontal group: 43 cm^3; neglect temporal group: 40 cm^3; RWN: 39 cm^3; $F(2,3) < 1$ *ns*], and the mean days after stroke [neglect frontal group: 59.5 days; neglect temporal group: 60 days; RWN: 63 days; $F(2,3) < 1$ *ns*].

The two groups of patients with neglect were well matched for degree of neglect (see Table 1). For example, on the star cancellation test the frontal patients found a mean of only 17 targets (range, 13–24) out of 54, all on the right side of the sheet. Similarly, the temporal patients found a mean of 16 out of 54 targets (range, 8–20), again all on the right side of the sheet.

Materials and Procedure

The apparatus, stimuli, procedures, and the analyses were all identical to those employed in the first study.

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