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Hemispatial neglect: its effects on visual perception and visually guided grasping

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Abstract

Hemispatial neglect is a neurological disorder characterized by a failure to represent information appearing in the hemispace contralateral to a brain lesion. In addition to the perceptual consequences of hemispatial neglect, several authors have reported that hemispatial neglect impairs visually guided movements. Others have reported that the extent of the impairment depends on the type of visually guided task. Finally, in some cases, neglect has been shown to impair visual perception without affecting visuomotor control in relation to the very same stimuli. While neglect patients may be able to successfully pick up an object they have difficulty perceiving in its entirety, it does not mean that they are picking up the object in the same way that a neurologically intact individual would. In the current study, patients with hemispatial neglect were presented with irregularly shaped objects, directly in front of them, that lacked clear symmetry and required an analysis of their entire contour in order to calculate stable grasp points. In a perceptual discrimination task, the neglect patients had difficulty distinguishing one object from another on the basis of their shape. In a grasping task, the neglect patients showed more variance in the position of their grasp on the target objects than their control subjects, with an overall shift to the relative right side of the presented objects. The perceptual and visuomotor deficits seen in patients with hemispatial neglect deficits may be the result of an inability to form good structural representations of the entire object for use in visual perception and visuomotor control.

Keywords: Hemispatial neglect; Visual perception; Grasping; Perceptual and visuomotor representations

1. Hemispatial neglect: its effects on visual perception and visually guided grasping

Visual neglect is a common neurological disorder in which patients fail to attend to, report or represent information appearing in contralesional hemispace, despite intact sensory processing and visual acuity. Hemispatial neglect is a common result of stroke, particularly after right-hemisphere brain damage (RHD), with reported incidence over 80% following lesions to the right middle cerebral artery [32]. Hemispatial neglect can be debilitating in everyday life. For example, after a right-hemisphere lesion, neglect patients may fail to notice objects on the left of a scene, words on the left of a page or food on the left of a plate. In the laboratory, these patients show an ipsilesional spatial bias in many simple paper-and-pencil tests; they deviate towards the right when asked to bisect a horizontal line at its midpoint and omit to copy or draw features on the left of a figure while preserving the corresponding features on the right.

One interpretation of the ipsilesional perceptual bias associated with hemispatial neglect is that representations of space become distorted following damage to the right (or left)-hemisphere. This distortion has been shown to be greater on the left than on the right side of space. Neglect patients, therefore, are unable to construct adequate perceptual representations of patterns in the left part of their world and may underestimate their extent relative to patterns on the right [17]. For example, patients with hemispatial neglect have been shown to judge horizontally oriented (but not vertically oriented) bar stimuli viewed on the left of a computer display as shorter than identical ones presented on the right [26], but see [13]. Milner and Harvey [26] found that the horizontally oriented bars were judged equal in size only when the left bar was up to 25% larger than the right bar. When novel shapes of different sizes were presented, the left shape had to be around 10% larger than the right shape to appear equal in size. When a landmark variant task was conducted where neglect patients were asked to

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point to the "shorter side" of a correctly pre-bisected line, they chose the left side as the shorter, indicating its lesser salience [18]. Similarly, when neglect patients were asked to extend a line on a paper to twice its length, they tended to over-extend it when drawing leftwards, but under-extend rightwards [7,8]. In short, it appears that neglect patients show a perceptual distortion of objects in the leftward parts of visual space, although the exclusivity of this distortion to neglect is still being debated.

Recent research indicates that the biases seen in both the size-matching tasks [13] and in the line-extension task [10] are associated with posterior lesions and with the presence of visual field defects. But is the visual field defect sometimes seen in neglect patients who show size distortion the underlying cause of that distortion or just a correlate of it—both symptoms being due to the location of the brain damage [29]? That such distortion certainly can occur as a result of damage that causes hemianopia but not neglect seems clear from the results of Ferber and Karnath [13] but this does not necessarily imply that the distortion in neglect is simply a consequence of a sensory visual loss. In a recent investigation, a left-hemisphere damaged patient was described who suffers from severe right visuospatial neglect and consequently, makes bisection errors in the leftward direction [29]. These visual size misperceptions were mirrored by a similar degree of tactile size misperceptions. The presence of this tactile misperception led Pritchard et al. [29] to conclude that their patient was unlikely to have been experiencing merely the perceptual consequences of damage to sensory visual cortex. Instead, the existence of tactile and visual distortions in neglect highlights the possibility of a distortion in an overarching spatial representation, or a rather high-level visuospatial disorder affecting visual imagery. If hemispatial neglect can disrupt visual and tactile representations, it may also disrupt other representations—like those needed for visuomotor control.

Traditionally, perceptual attention [2,21] and/or motor theories [6,25] have been used to explain the deficits associated with hemispatial neglect. Recent studies, however, have challenged the simple attention/motor dichotomy [8,23,30]. The distinction itself seems to have lost clarity since many of the "perceptual" tasks that are impaired by hemispatial neglect actually involve visuomotor transformations. These visuomotor transformations are carried out in the dorsal cortical stream of projections from primary visual cortex to posterior parietal cortex: whereas the mechanisms in the ventral stream, which projects from primary visual cortex to the inferotemporal lobe, underlie visual perception [14]. Mechanisms operating upon various processing stages ranging from perception to action have been used to explain neglect [1]. It is possible that hemispatial neglect could affect both streams—not only impairing visual perception but also the underlying mechanisms controlling visually guided action.

Several authors have shown that hemispatial neglect impairs the ability to plan and initiate visually guided leftward limb movements [3,22] and eye movements [4,19,29]. For example, Ro et al. [30] found an ipsilesional bias in saccadic eye movements associated with hemispatial neglect that could not be attributed to deficient visual perception. These studies suggest that in the visuomotor domain, information on the contralesional side is incompletely processed, if at all, in patients with hemispatial neglect [5].

In contrast, Pritchard et al. [28] found that a neglect patient (EC) was able to skillfully grab a target, whether it was placed in her right or left hemispace, despite impaired perceptions of its size. EC showed no significant difference in maximum grip aperture attained when reaching to the left and when reaching to the right. When EC was asked to estimate the size of the target objects, however, she underestimated the size of the target when it was placed on her left. Pritchard et al. [28] proposed that grasping actions in their patient were based on intact dorsal representations mediating on-line visually guided actions and that the neglect shown in the size judgment task reflected a distortion of more ventral representations. It appears that neglect can influence the visual perception of size without affecting visuomotor control in relation to the very same stimuli.

Some researchers have reported that different degrees of impairment are associated with different visually guided movements. Robertson et al. [31] found neglect patients who showed a strong rightward bias when pointing to the judged center of a rod but showed little neglect when a grasp response was used. This advantage for grasp over pointing responses occurred only when performance was guided by on-line visual feedback. These results were replicated by Edwards and Humphreys [12], who found that neglect patient, MP, showed neglect in his pointing movements but was within the control range in his grasping—actually bisecting rods slightly to the left of the true center during a grasp. As with the size estimates in the Pritchard et al. [28] study mentioned earlier, the pointing bias seen in these studies may result from damage to perceptual representations. While this possibility seems counterintuitive, one must keep in mind the fact that perceptual representations are not only utilized for object perception but also for "perceptual–motor" tasks like pointing. The pointing tasks described earlier require patients to "show" the experimenter the middle of the rod—a very perceptual concept. Hemispatial neglect may, therefore, disrupt perceptual representations while sparing the visuomotor networks guiding grasping [27].

While some neglect patients may be able to successfully pick up an object they have difficulty perceiving in its entirety, it does not mean that they are picking up the object in the same way that an intact individual would. For example, in the Pritchard et al. [28] study, the valid grip scaling shown by EC could exist even if she had only perceived the right half of the circular target. What if the entire object needed to be considered in order for a stable grasp to occur? In the current study, patients with hemispatial neglect were presented with irregularly shaped objects that lacked clear symmetry and required an analysis of their entire contour in order to calculate stable grasp points. It was predicted that these irregularly shaped objects would reveal that hemispatial neglect can not only impair perception but can also have adverse consequences for visuomotor control—causing patients with hemispatial neglect to select less stable grasp points than their control subjects.

2. Methods

2.1. Subjects

Six males with left hemispatial neglect as a result of a right-hemisphere lesion (mean age = 67.3 years), six normal, non-neurological, control subjects (three males and three females; mean age = 64 years) and three RHD control subjects without hemispatial neglect (two males and one female; mean age = 46.7 years) consented to participate in the experiment. All subjects were right-handed and had normal or corrected-to-normal visual acuity. All of the neglect patients showed clear evidence of left-sided neglect and performed outside normal limits on the formal subtests of the Behavioral Inattention Tests (BIT, Thames Valley Test Company, 1987), which includes line crossing, letter and star cancellation, line bisection, figure and shape copying and free drawing tasks. Details of the neglect patients' lesions are presented in Table 1 (also see Fig. 1 for MR/CT scans). Details of the RHD controls' lesions are also presented in Table 1. The RHD controls all scored within the normal limits on the subtests of the BIT.

2.2. Apparatus and materials

Two sets of 12 shapes, constructed out of wood 6 mm thick and painted enamel white (see Fig. 2), were used in a same/different discrimination task and a grasping task. The shapes were modeled after templates used by Blake [9] to develop algorithms for the control of grasping in two-fingered robots working in novel environments and have previously been used successfully in reaching and grasping experiments with patient groups [15]. These shapes have smoothly bounded contours and lack clear symmetry; the determination of stable grasp points therefore requires an analysis of the entire contour envelope of the shape. Subjects wore finger cots, which were inked, on the thumb and index finger of their right hand.

Table 1
Demographic and lesion details for neglect patients and right-hemisphere brain damage (RHD) control subjects

Patient	Group	Age	Lesion volume	Areas involved
FG	Neglect	67	110 cm^3	Right: parietal and frontal
FT	Neglect	66	175 cm^3	Right: parietal and frontal
JS	Neglect	71	89 cm^3	Right: parietal, frontal, and temporo-occipital
MA	Neglect	76	61 cm^3	Right: frontal, temporal
RB	Neglect	67	90 cm^3	Right: parietal, temporal, and occipital
TG	Neglect	57	1.5 cm mass	Right: parietal
CH	RHD	58	Unavailable	Right: parietal
JM	RHD	56	126 cm^3	Right: fronto-temporal, thalamus, and basal ganglia
RD	RHD	26	252 cm^3	Right: fronto-temporal (craniotomy)

2.3. Design and procedure

Each of the 96 trials consisted of a discrimination task followed by a grasping task. The subjects were seated at a table covered with a black cloth. A pair of shapes was placed 10 cm apart in front of the subjects along their vertical midline; the closer position was 20 cm from the edge of the table. In the discrimination task, the subjects were required to visually determine if the two shapes were the same or different. The relative orientation of the shapes varied randomly from trial to trial, with their principal axis being rotated in the plane of the table either 0, 90, 180, or 270°. Each shape was presented eight times in both the close and far positions. The two shapes were identical on half the trials. The grasping task required subjects to pick up a target shape with the thumb and index finger of their right hand. The subjects were instructed to reach as quickly, accurately, and "naturally" as possible.

At the start of each trial, the experimenter instructed the subjects to close their eyes. When the subjects' eyes were closed, the experimenter positioned the two shapes for the discrimination task. Once the shapes were in position, the subjects were instructed to open their eyes and report whether the two shapes were the same or different. After their response, the experimenter instructed the subjects to close their eyes once again and then removed one of the two shapes. The removal of the shape was counterbalanced for the near and far position. After the shape was removed, the experimenter instructed the subjects to open their eyes and pick up the remaining shape. The centers of the two ink marks on the object boundary where the thumb and index finger first contacted the shape were then recorded on prepared templates. The ink marks were then removed from the shapes with isopropyl alcohol.

3. Results

The patients with hemispatial neglect had difficulty distinguishing one object from another on the basis of their shape and produced significantly more perceptual errors (69.8% correct) in the discrimination task than the intact control subjects (98.8% correct) ($P < 0.01$) and the RHD control subjects (92% correct) ($P < 0.01$) ($F_{(2,12)} = 33.68$, $P < 0.0001$). There was no significant difference in the number of perceptual errors produced by the intact control subjects

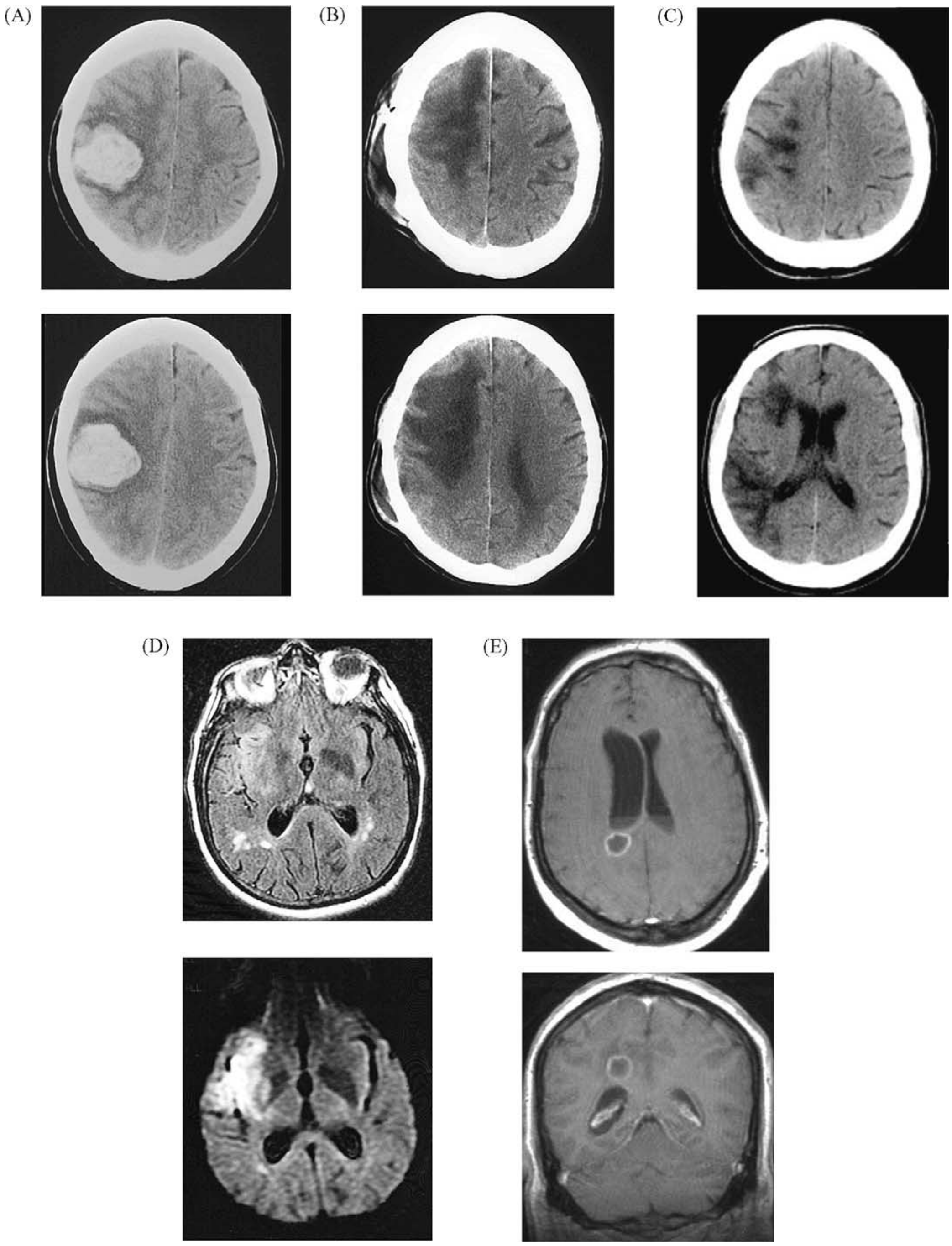

Fig. 1. Neuroimaging data for five of the six patients with hemispatial neglect; the images were obtained by magnetic resonance imaging and computerized tomography. (A) FG; (B) FT; (C) JS; (D) MA; (E) FG. Images for patient RB were not available for publication. Following radiological convention, the right side of the brain is on the left side of the photograph.

and the RHD control subjects ($P > 0.05$). In fact, there were no significant differences between the intact control subjects and the RHD control subjects in any of the dependent measures used in this experiment. For that reason, the comparisons between control groups will not be discussed individually.

Overall grasp performance was quantified by measuring the shortest distance between the 'grasp line' (joining points where the thumb and index finger first made contact with the shape) on each trial and the object's center of mass. The distance of this grasp line from the center of mass can be used as a measure of grasp stability [15]. A stable grasp will produce a grasp line that tends to pass through or close to the center of an object's mass. As a first measure of grasp stability, we compared all of the reaches produced by the subjects that resulted in grasp lines that fell within 2 mm

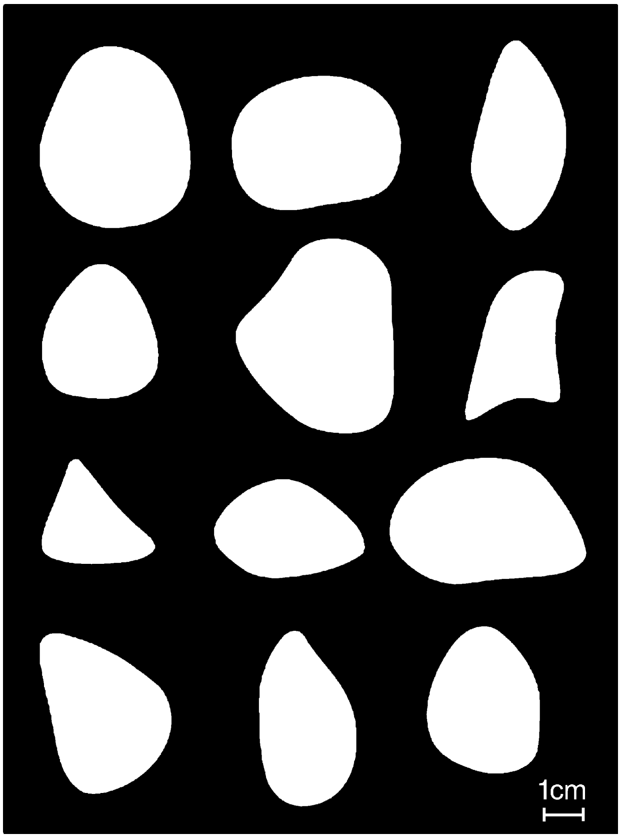

Fig. 2. The 12 different shapes used in the visual discrimination task and in the grasping task.

of the center of mass, a zone in which the control subjects produced the majority of their grasping points. Neglect patients produced significantly fewer grasp lines that fell within this zone (27.8) ($P < 0.01$) than the intact control subjects (55.7) or the RBD controls (58.6) ($F_{(2,12)} = 44.62$, $P < 0.0001$). Moreover, when all grasp lines were considered, the neglect patients were found to produce grasp lines that totaled over twice the distance from the center of mass of the object as those produced by the intact control subjects ($P < 0.01$) and the RHD control subjects ($P < 0.01$) ($F_{(2,12)} = 20.71$, $P < 0.0001$) (see Fig. 3). The following observations, regarding both the intact control subjects and the RHD control subjects, were also made. First, the grasp lines often corresponded to the axes of minimum or maximum diameter of the object. Second, the grasp points were often located on regions of the object boundary that would be expected to yield the most stable grip [9,20]—regions of maximum convexity or concavity. Neglect patients, on the other hand, often chose unstable grasp points, particularly when the longest axis was presented in the horizontal plane.

To determine if there was an ipsilesional bias in neglect patients' grasping position on the target shapes, the number and magnitude of grasp lines were calculated that fell to the right or left of the center of the object's mass in the 45 trials in which the shapes were presented with their longest axis in the horizontal plane. Since we were primarily interested in the grasp lines when they fell to the right or left of center, grasp lines that crossed directly through the center of mass (0 mm) were not included in these calculations. It should be pointed out, however, that the neglect patients produced fewer of these 0 mm grasp lines on average (3.17) than their intact controls (10.17) ($F_{(1,10)} = 5.04$, $P < 0.05$). As can be seen in Fig. 4, while the number of grasp lines to the left of center did not differ between neglect patients and the intact control subjects ($P > 0.05$) or the RHD control subjects ($P > 0.05$), neglect patients produced significantly more grasp lines to the right of center than either their intact

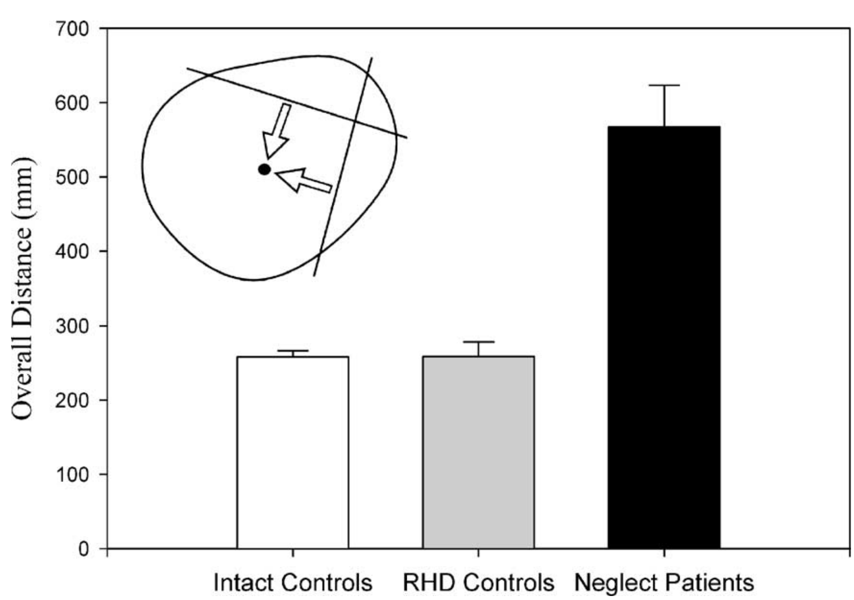

Fig. 3. The overall distance between the grasp lines and the center of mass of the shapes for the neglect patients, the intact control subjects and the right-hemisphere brain damage (RHD) control subjects during all 96 trials.

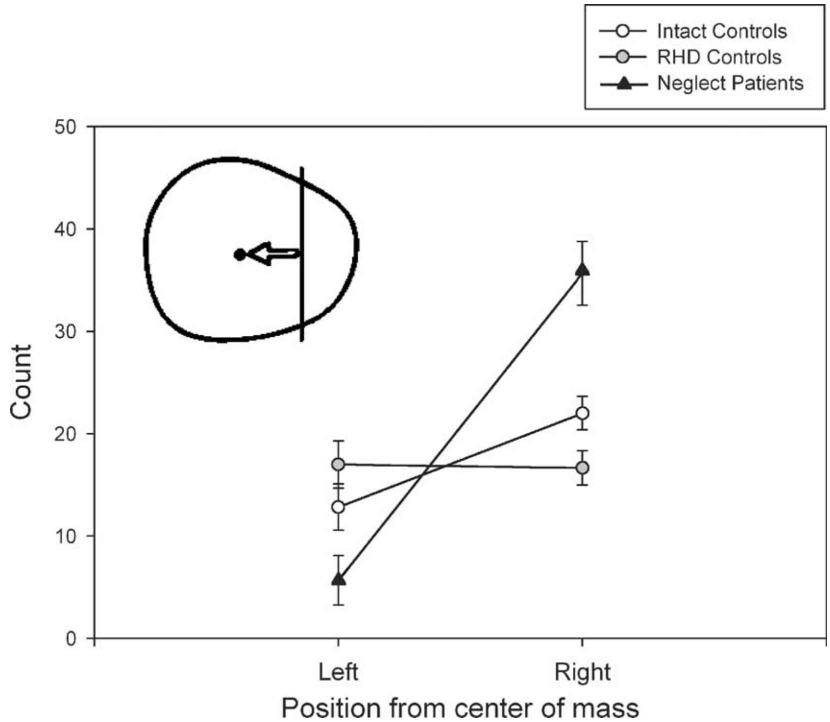

Fig. 4. The number of reaches to the right and left of the center of mass for the neglect patients, the intact control subjects and the RHD control subjects during the 45 trials in which the shapes were presented with their longest axis in the horizontal plane.

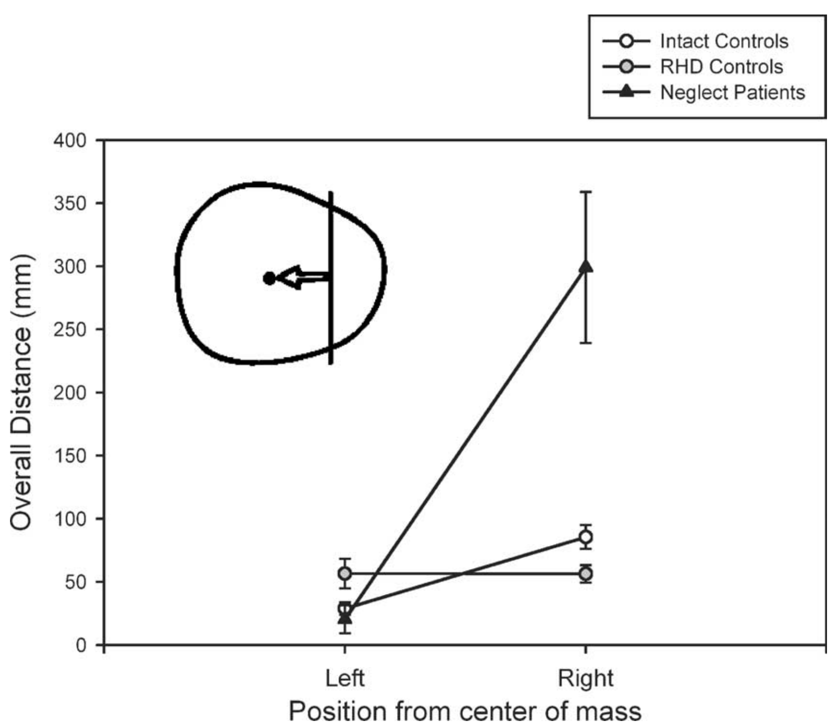

Fig. 5. The overall distance between the grasp lines produced to the right or left of center and the center of mass of the shape for the neglect patients, the intact control subjects and the RHD control subjects during the 45 trials in which the shapes were presented with their longest axis in the horizontal plane.

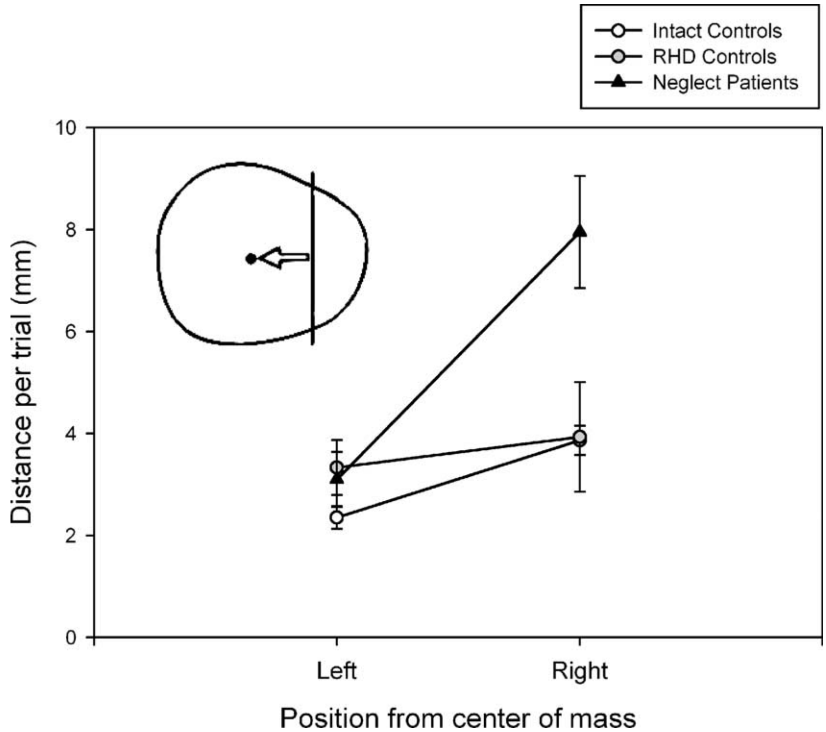

Fig. 6. The distance per trial between the grasp lines produced to the right or left of center and the center of mass of the shape for the neglect patients, the intact control subjects and the RHD control subjects during the 45 trials in which the shapes were presented with their longest axis in the horizontal plane.

control subjects ($P < 0.05$) or their RHD control subjects ($P < 0.05$) ($F_{(2,12)} = 12.04$, $P < 0.005$). The number of grasps produced by the intact control subjects ($P > 0.05$) and the RHD control subjects ($P > 0.05$) to the left or right of center did not differ significantly.

The same pattern can be seen in both overall distance ($F_{(2,12)} = 8.91$, $P < 0.005$) (see Fig. 5) and the distance per trial from the center of mass ($F_{(2,12)} = 5.83$, $P < 0.05$) (see Fig. 6). For both measures, the neglect patients, their intact controls and the RHD controls did not differ for grasps made to the left of center. When the grasps were to the right of center, however, both the overall distance ($P < 0.01$) and the distance per trial ($P < 0.01$) produced by the neglect patients were greater than that of their intact control subjects and the RHD controls. There was no significant difference in the magnitude ($P > 0.05$) or magnitude per trial ($P > 0.05$) of grasps produced to the left or right of center by the intact control subjects or the RHD control subjects.

Neglect severity, as reflected in the BIT scores, correlated significantly with the number of correct responses made by subjects ($r = 0.68$, $P < 0.01$), the overall distance of the grasp lines from the center of mass ($r = -0.60$, $P < 0.05$), the number of grasp lines produced to the right of center ($r = -0.56$, $P < 0.05$), the magnitude of the reaches to the right of center ($r = -0.54$, $P < 0.05$), and the magnitude per trial for the reaches made to the right of center ($r = -0.55$, $P < 0.05$). In short, the severity of hemispatial neglect, as scored by the BIT, significantly correlated with the severity of the perceptual and visuomotor deficits seen in the visual discrimination and grasping tasks.[1]

Finally, there was a strong rank order correlation between the number of patients' grasp lines to the right of center and the overall distance ($r_s = 0.94$, $P < 0.005$) and distance per trial ($r_s = 0.94$, $P < 0.005$) of those rightward grasp points. In other words, the patients who produced the largest number of rightward grasp lines were the ones who produced the largest deviations to the right. This was not the case for the intact control subjects ($r_s = 0.77$, $P > 0.05$; $r_s = 0.77$, $P > 0.05$, respectively) nor the RHD control subjects ($r_s = -0.87$, $P > 0.05$; $r_s = -0.87$, $P > 0.05$, respectively). Individual results for all the subjects are summarized in Appendix A.

[1] A trial-by-trial correlational analysis of the perceptual discrimination performance and the grasping performance was not possible within the current experimental design. Although subjects performed the perceptual discrimination task interleaved with the grasping task, the tasks were done sequentially. Additionally, because the perceptual discrimination involved two shapes but only one shape was on the table during the grasping task, it cannot be assumed that the neglect patients were having the same perceptual experiences in the two tasks. Nevertheless, examining subjects' performance on the discrimination task provides some insight into the determinants of performance on the reaching task. All subjects performed both tasks so that we might have a within-subject comparison of the subjects' perceptual and reaching behavior, but a trial-by-trial correlational analysis was not considered conceptually legitimate.

4. Discussion

While some studies have reported that neglect patients are able to pick up an object placed in front of them, even when they have difficulty making accurate perceptual judgments about that object, it does not mean that they are performing the task the same way that an intact individual would. In the current study, a visual discrimination task and a grasping task were conducted utilizing irregularly shaped objects that lack clear symmetry and require an analysis of their entire contour in order to calculate stable grasp points. Patients with hemispatial neglect had difficulty distinguishing one object from another on the basis of their shape in the visual discrimination task. When the neglect patients were asked to pick up the shapes, they could do so successfully, consistent with previous reports. However, detailed examination of their grasping behavior revealed that the patients showed more variance in the position of their grasp on the objects than their control subjects, with an overall shift to the relative right side of the presented objects. These perceptual and visuomotor deficits may be the result of an inability to form complete structural representations of the entire object for use in visual perception and visuomotor control. The patients appeared to be treating an object as if its center of mass had been shifted to the right (i.e. as if the left portion of the object was ignored or less salient) [16]. Where along the processing streams to visual perception and the visual control of action does this failure take place?

Since both perception and action are affected, one might expect that the impairments take place "early on" in the processing streams and that the sensory information used to build the perceptual and visuomotor representations is faulty or incomplete. Neglect, however, is a rather paradoxical disorder in the sense that patients remain unaware of, or unable to represent, contralesional stimuli, despite having well preserved sensory mechanisms for processing their physical and semantic properties. In fact, several experiments have shown that the color, form, identity and meaning of neglected visual stimuli can sometimes be activated unconsciously [24]. It is possible then, that the deficits associated with hemispatial neglect result from damage that is "higher up" the processing stream (i.e. in the parietal or frontal lobes).

In agreement with previous studies that have shown intact grasping in hemispatial neglect, our investigation found that neglect patients were able to successfully pick up the objects placed in front of them. Where we differ, is the reported ability of neglect patients to grasp objects across their center of mass. Those studies in which neglect patients were able to successfully grasp the center of an object have all utilized simple, symmetrical objects—like rods. One reason why neglect patients may be able to grasp the center of a rod in these studies is because they show a preserved effect of symmetry [11]. Since symmetry depends on the correspondence between reflected sides, sensitivity to symmetry requires representation of both the right and left sides of shapes at an early stage of processing. Neglect of the left side of the figure must arise at a subsequent stage of attending it, which would explain the inability of neglect patients to make explicit perceptual judgments. It would also explain their difficulty in pointing to the center of a rod—a "perceptual" task. When hemispatial neglect patients were asked to pick up the simple symmetrical rod, enough information may have been available at an early stage of processing to allow for a correctly programmed grasp. In future experiments, both non-symmetrical and symmetrical objects should be presented to neglect patients to determine whether the symmetry of the graspable object is indeed responsible for spared visuomotor control in neglect.

Another factor that should be considered is that top–down instructions from the experimenter may also play a role. For example, in the rod tasks discussed earlier, the neglect patients were asked specifically to pick up the rod at its center. Additionally, as part of their rehabilitation, neglect patients are strongly encouraged to make more leftward movements. It is possible that a higher order influence of experimenter instructions resulted in the neglect patients making more of a leftward movement than they would have left to their own devices. In the current study, subjects were only told to pick up the object using their index finger and thumb and were never given specific instructions as to where they should position their fingers on the object—a more "natural" situation.

Although we have proposed several explanations for the inconsistencies in the existing literature, it is possible of course, that there is no unified explanation and the studies reflect the heterogeneity of performance in the neglect population. The perception–action dissociation reported in the other studies may occur selectively in particular patients (e.g. due to the site and size of the lesion) and it is possible that the perception–action dissociation might persist in these individuals even with shapes such as those used in the current study. Whether such a dissociation exists is an empirical question and remains to be answered. It is worth noting, however, that the current study has presented results from six neglect patients, and not one of them has exhibited normal grasping with impaired visual discrimination. In summary, the use of irregularly shaped objects that lack clear symmetry produces visual perception and visuomotor deficits in patients with hemispatial neglect in both visual discrimination and grasping tasks.

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Appendix A

Subject	Group	Count		Magnitude (mm)		Magnitude/count		Overall magnitude (mm) (96 trials)	Correct perceptual discrimination (96 total)
		Left	Right	Left	Right	Left	Right		
RB	Neglect	17	23	75	99	4.4	4.3	341	77
JS	Neglect	3	41	15	376	5	9.2	645	52
MA	Neglect	1	43	2	495	2	11.5	718	74
FG	Neglect	7	30	17	176	2.4	5.9	522	71
FT	Neglect	4	38	7	266	1.8	7	510	61
TG	Neglect	2	39	6	382	3	9.8	666	67
CB	Control	16	18	36	83	2.3	4.6	228	93
MAT	Control	20	24	36	83	1.8	3.5	254	94
MW	Control	12	24	22	108	1.8	4.5	274	96
AH	Control	4	24	12	95	3	4	255	96
JS	Control	10	16	22	43	2.2	2.7	253	94
NL	Control	15	26	45	101	3	3.9	286	96
CH	RHD	17	15	75	70	4.4	4.7	294	89
RD	RHD	21	20	60	48	2.9	2.4	255	87
JM	RHD	13	15	35	51	2.7	3.4	227	89

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