Distortion of size perception in visuospatial neglect

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Background: A number of studies have shown that most patients with symptoms of unilateral (left-sided) visuospatial neglect make consistently rightward errors when attempting to bisect a horizontal line at its midpoint. One possible interpretation of this impairment is that such patients misperceive the left half of the line: that is, that they underestimate its extent relative to the right half.

Results: We have carried out direct tests for such a perceptual distortion in three neglect patients by asking them to make matching judgements on pairs of horizontal rectangles, vertical rectangles or nonsense shapes, of varying relative size, presented on a computer screen. We report here that all of the patients tested showed a significant and substantial relative underestimation of the horizontal extent or area of stimuli presented on the left side of their egocentric space. There was no such misperception of vertical extent.

Conclusions: It is suggested that size perception may be partially determined by a representational system that is anatomically centred in the parieto-temporal region of the brain. The results are interpreted in terms of damage to this system in neglect patients.

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Background

The neurological condition of unilateral spatial neglect typically follows large brain lesions, resulting for example from a major stroke, that include the region at the border of the temporal and parietal lobes of the human right hemisphere (Fig. 1). The symptoms of neglect are many and various, but always include a tendency to ignore objects and parts of objects on the patient's contralesional (left) side of space. The most convenient and commonly used quantitative test for the severity of neglect is that of line bisection. It is now well-established that most patients who are diagnosed as having unilateral visuospatial neglect tend to make substantial rightward errors when asked to bisect a horizontal line on paper [1–4].

It has been found that most neglect patients make these errors for broadly perceptual or visual-attentional reasons, causing them to misjudge the midpoint of the line [5–8]. This 'perceptual' form of neglect seems to be mainly associated with damage that includes the posterior regions of the right hemisphere, as indicated in Figure 1. It should be noted, however, that a minority of neglect patients are instead dominated by a motor bias, which seems to shift their bisection responses directly in a rightward direction [5,7,8]. This 'directional-motor' neglect is generally associated with frontal and/or basal ganglia damage.

The present experiment was designed to investigate the nature of the disorder suffered by perceptual neglect patients. It was hypothesized that they might, either through an attentional or a representational failure, actually perceive linear extents in the left half of egocentric space as shorter than equivalent extents in the right half of space. We have already presented evidence that neglect patients judge the left half of a single line as shorter than its right half [6,8]. This provides a direct explanation of their tendency to bisect a line to the right of centre. Following the suggestion by Gainotti and Tiacci [9], we proposed that neglect might be associated with a more generalized 'shrinkage' in size perception in the affected half of space, and we presented preliminary evidence for this in a single patient [6].

Here we extend those observations by describing data on a group of three neglect patients who all showed rightward line bisection errors. We presented pairs of computer-generated rectangles and nonsense shapes of different sizes on a television screen, to examine whether neglect patients consistently judge stimuli viewed on the

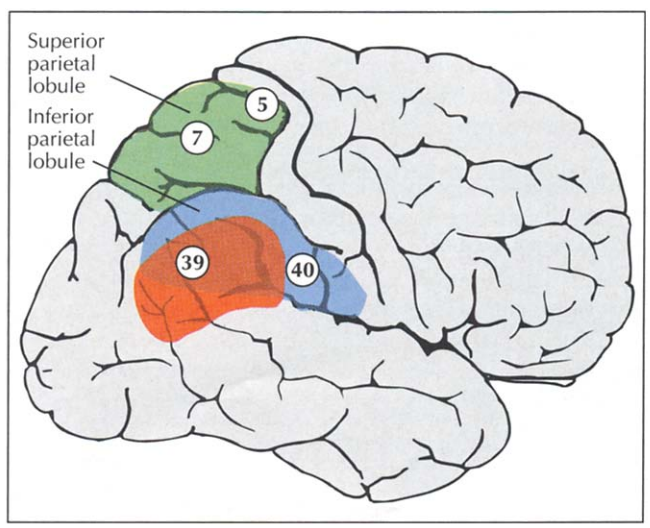

Fig. 1. Diagrammatic representation of the right hemisphere of the human brain showing the two main parts of the parietal lobe, and indicating (in red) the region typically damaged in patients suffering from visuospatial neglect. The numbers indicate Brodmann's cytoarchitectonically identified areas. After [21].

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left as shorter or smaller than similar ones presented on the right. In all of these tests, our primary interest was to see whether the patients made 'constant errors' (that is, systematic biases in judgement), rather than 'random errors' (that is, increased variability of judgement). As well as comparing the neglect patients against a group of other patients who have suffered similar right-hemisphere strokes, but who do not display neglect, we have included control groups of left-hemisphere stroke and matched normal subjects, in order to be able to broaden our conclusions.

Results

Line bisection

The three neglect patients (MJ, BN and JW) each bisected lines consistently and substantially to the right of the midpoint of a 200 mm line (mean errors +27 mm, +42 mm and +11 mm, positive scores indicating rightward errors). These errors contrast with means of +0.1 mm (standard deviation (SD) 3.5; range −5.5 mm to +4.0 mm) for the right-hemisphere patients without neglect, and −2.5 mm (SD 3.4; range −6.6 mm to +3.2 mm) for the left-hemisphere patients. In all cases, the patient used his/her ipsilesional hand. The healthy controls made mean errors of −1.5 mm (SD 2.5; range −6.3 mm to +5.3 mm), averaged across the two hands. (For more details, see [8].)

Constant errors in left–right comparisons

During the main part of the study, test stimuli were presented pairwise on a computer screen for comparison: the patient was asked to indicate which stimulus was larger (or smaller, in different test sessions) by pressing a keyboard arrow key. The results were scored in a standardized fashion for each stimulus set, yielding either a positive score, indicating the magnitude of any left-side stimulus underestimation, or a negative score, indicating the reverse tendency.

The results for horizontal rectangles are shown in Figure 2a. It can be seen that each of the three neglect patients needed the leftward of two rectangles to be substantially longer than the one on the right in order for the two to be judged as equivalent in length. In contrast, none of the normal subjects or control patients without neglect showed a comparable leftward underestimation, the tendency, if anything, being in the opposite direction. (In fact, 11 of the 12 healthy controls gained small negative scores, and none went positive: $p < 0.001$, binomial test.) Statistical comparison of the neglect group with each of the control groups of subjects indicates a highly significant difference in each case (Student's t test giving: $t(13) = 3.23$, 3.11 and 3.28; $p < 0.005$.) Interpolation of the data allows the point of subjective equality (PSE) to be calculated for each patient: these indicate a relative left-stimulus underestimation of 15 %, 20 %, and 25 %, for patients MJ, BN and JW, respectively.

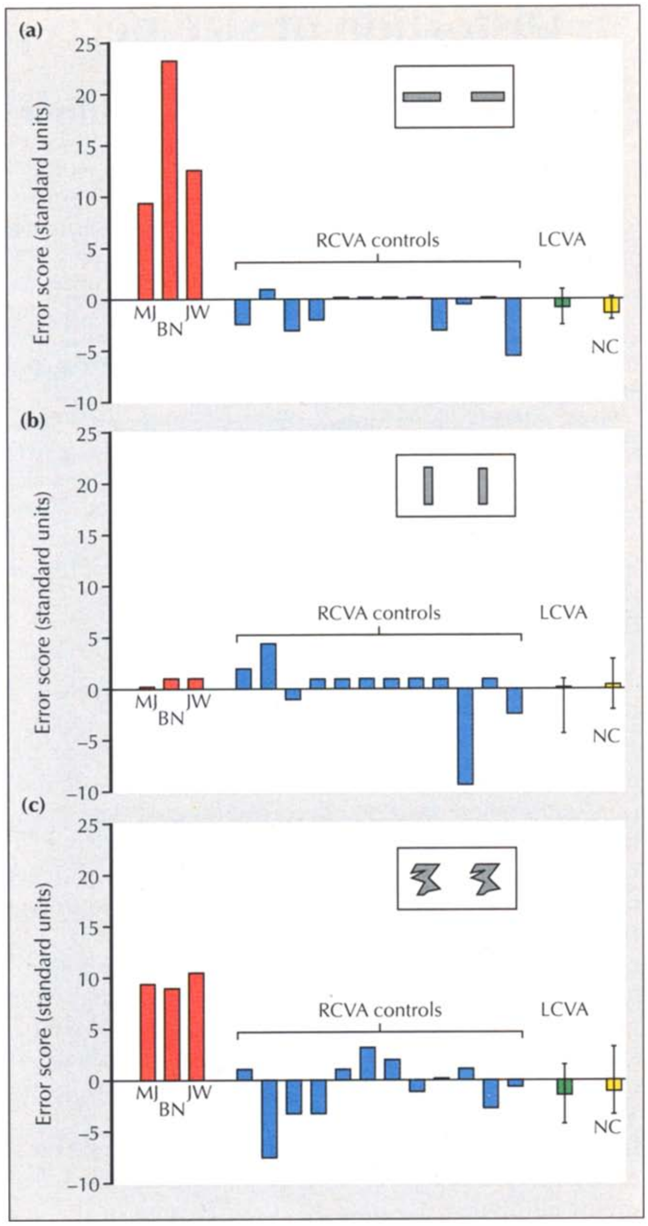

Fig. 2. (a) 'Constant errors' in matching horizontal rectangles presented one on the left and one on the right of a computer screen. The ordinate represents the extent to which the left rectangle had to be longer than the right rectangle in order to appear of equal length to the subjects tested (arbitrary standard units). The three patients with visuospatial neglect (MJ, BN and JW) are each shown individually, as are the 12 control patients with right hemisphere stroke but no neglect (RCVA controls). The mean results (+/− range) for the control groups of subjects with left-hemisphere stroke (LCVA) or without neurological illness (NC) are shown on the right. **(b)** Constant errors in matching vertical rectangles presented on the left and right of a computer screen. Conventions as in (a). **(c)** Constant errors in matching nonsense shapes presented on the left and right of a computer screen. The ordinate represents the extent to which the left shape had to be larger than the right shape in order to appear of equal area. Conventions as in (a).

These results contrast with those for vertical rectangles, which are shown in Figure 2b. It can be seen that, in this case, the three neglect patients were able to make left–right comparisons of rectangles quite accurately.

There were no significant differences between the neglect group and any of the control groups ($t(13) = 0.58$, 1.18, and 1.70; $p > 0.05$).

As shown in Figure 2c, however, nonsense shapes yielded results similar to horizontal rectangles. Each of the three neglect patients needed a shape on the left to be substantially larger than one on the right in order to appear of equivalent area. They differed highly reliably from each of the three control groups ($t(13) = 12.43$, 11.08 and 13.42; $p < 0.0001$ in each case). The PSEs indicate a mean relative left-stimulus linear underestimation of 15% for each of the three neglect patients; none of the normal subjects or patients without neglect showed such a large leftward underestimation.

Control tests

In order to exclude failures of perceptual matching unrelated to the left–right dimension of space, an equal number of tests were administered in which subjects were presented with stimuli in the up–down dimension. No differences were found between the neglect patients and the control groups in terms of constant error (for example, there was no underestimation of length in upper space, relative to lower). In addition, we examined the unsigned ('random') errors made by the normal control subjects when making left–right comparisons of horizontal or vertical rectangles. Their mean error score for the left–right matching of vertical stimuli (0.91; SD 1.08) was identical to that for matching horizontal ones (0.91; SD 1.31).

Discussion

The present results indicate that three right-hemisphere damaged patients with visuospatial neglect all perceived the horizontal extent of stimulus shapes on the left side of their egocentric space as shorter than that of ones on the right. This perceptual distortion of horizontal extent is presumably sufficient to account for the fact that the three patients also underestimated the area of nonsense shapes on the left. Yet this perceptual bias was absent when vertical extent was being judged. It could, of course, be argued that the task of matching vertical lines between left and right was simply geometrically easier than that of matching horizontal lines. However, this interpretation is not supported by our analysis of the unsigned errors made by the control patients (see above), which shows that the two tasks were of similar intrinsic difficulty.

Although our three neglect patients were unselected consecutive cases, there is independent evidence that all of them were of the 'perceptual' type [5]; that is, they appear to bisect lines rightwardly because of faulty stimulus processing, rather than because they misdirect their responses. The evidence for this is presented elsewhere [8]. In brief, the patients were shown centrally-prebisected lines and asked to point to the end that was closer to the bisection mark. A bias to respond rightwards would predict rightward pointing, but instead these patients pointed leftwards, indicating that they misperceived the point of bisection. We would predict that neglect patients of the less common 'directional-motor' type (such as patient EL in [8]) would not show the perceptual effects we have described in this paper.

We also examined whether our neglect patients show any systematic biases in making comparisons within a range of other perceptual dimensions, using sets of stimuli differing in lightness, dot density, spatial frequency and orientation. There were no significant differences between the neglect patients as a group and any of the other groups on any of these tasks. Nevertheless, when patches composed of different densities of random dots were presented, two of our neglect patients (MJ and BN) did show a leftward overestimation of dot density — they saw the dots on the left as being closer together than those on the right. Their scores did not overlap with the range of normal or left-hemisphere subjects, but one of the right-hemisphere control patients (JB) showed an even higher score than these two neglect patients. Interestingly, however, this patient had shown some indication of neglect after her stroke, although this had recovered by the time of testing.

It should be noted here that, although there has been a previous report [10] of 'spatial compression' in a patient with visuospatial neglect (PP), the phenomenon seen there was not one of greater compression on the left than on the right. PP's subjective space seemed to have been compressed uniformly — just as when a compression spring is pushed from left to right the coils remain equally spaced. Thus, PP would not be expected to judge dot patterns to be denser on the left than on the right, but simply as denser than normal wherever she saw them. It is unclear whether our patients would have shown a spatial compression effect similar to that seen in PP. Although the misperception of size that we have found in our patients would not be predicted from such an effect, it would not be incompatible with it.

Our data suggest that horizontal size is miscomputed in leftward parts of the visual array. It is notable that this occurs under free viewing conditions, in which an extended object is presumably 'constructed' from a sequence of snapshots separated by saccadic eye movements. In fact, perceptual neglect patients bisect very short lines, which can be encompassed in a single ocular fixation, quite normally (A.D.M., M.H. and R.C. Roberts, manuscript submitted). It may be this process of synthesis (for leftward parts of space) that is defective in our patients. This idea is related to previous theoretical accounts of visuospatial neglect that have postulated representational deficits of different kinds [11–13].

The relative rarity of severe neglect after left-hemisphere damage suggests that this hypothesized representational system is better developed in the human right hemisphere than in the left. If so, then normal subjects should tend to perceive rectangles presented on the left (which would be processed primarily in the right hemisphere) as longer than similar stimuli on the right (which would be processed primarily in the left hemisphere). This is precisely what we found in our healthy control subjects: they judged identical horizontal rectangles to be slightly longer on the left than on the right side, even though central fixation during stimulus presentation was not required. This finding also agrees with our previous report that the right half of a line pre-transected at its midpoint tends to appear shorter than the left half in young normal subjects [14], and with the occasional report that lines are bisected more often to the left than the right of centre by normal subjects [14,15].

Conclusions

The results that we have described indicate that patients with right hemisphere damage and left visuospatial neglect underestimate the size of forms seen on the left side of egocentric space. This evidence is consistent with the view that such patients fail to construct adequate representations of patterns in the leftward parts of their egocentric space.

Materials and methods

Procedure

Patients were seated at a distance of approximately 60 cm in front of a 14-inch long-persistence colour graphics monitor. Patterns were constructed using a Pluto graphics system (IO Research Ltd), and were located symmetrically on the screen, their centres lying 4.5 cm up, down, right or left from the centre. A pseudorandom series of identical or differing pairs of patterns was presented. Up–down comparisons were used as a control condition and randomly interspersed with left–right comparisons. Subjects were falsely informed that none of the pairs were identical, and were asked to indicate on each trial which one of the two patterns appeared to be longer, which larger and so on, by pressing one of the four keyboard 'arrow' keys. These keys were placed centrally in front of the monitor screen and the rest of the keyboard was covered. There was no time constraint and the patterns remained visible until a permitted key was pressed (either the left–right key for laterally presented patterns, or one of the up–down keys for the vertical pairs). There then followed an interstimulus interval of one second.

To control for response bias, all patients were tested twice, under opposing response instructions. Thus, in one session they were asked to judge which stimulus appeared larger or longer, and on the other to indicate the stimulus that appeared smaller or shorter (and so on). Patients with a truly perceptual bias should respond rightwards on the 'larger' instructions and leftwards on the 'smaller' instructions. To prevent interference between the opposing instructions, the two sessions of testing were separated by a minimum time interval of one week. The order of testing was balanced across subjects as far as possible.

Materials

Seven different sets of patterns were created: horizontal rectangles, vertical rectangles, nonsense shapes, gratings of different spatial frequency, random dots with differing density, oblique arrays of differing orientation, and grey-level patches with differing lightness levels. For each stimulus type, a prototype was created, and on all trials this was presented in one half of the screen (left, right, top or bottom), in combination with either an identical pattern or a different pattern derived from it, in the other half of the screen.

The prototype horizontal rectangle was 4 cm long and 0.5 cm wide, and presented in outline form. Ten shorter rectangles were derived from it, each having the same width but varying in length from 95 % to 50 % of the prototype, in steps of 5 %. All the possible combinations of these 10 lines with the prototype, plus one identical pairing, in left–right and up–down orientations, produced 42 pairings, which were presented in pseudorandom order. Similarly, vertical rectangles of 4 cm length and 0.5 cm width, and shorter shapes derived from them, formed another set of 42 pairs. In one test session, patients were instructed to indicate the longer line, and in the other session the shorter line.

The prototype of the nonsense shape was again drawn as an outline, and consisted of an irregular 11-sided polygon covering an area of 4 sq cm. The 10 comparison patterns retained the prototype shape, but ranged in area from 95 % of the prototype down to 50 %, again yielding a total of 42 pairs. Patients were instructed to indicate the 'larger' (or in the other session the 'smaller') shape.

Scoring procedure

As the different stimulus series were not matched for discrimination difficulty, each subtask was analyzed separately. A measure of perceptual bias which took into account all of the patient's errors was arrived at as follows. When an error occurred on a given trial, it was assigned a value of $N+1$, where N is the number of steps by which the patterns differed on that trial. Rightward errors (such as when the patient judged a line longer on the right, although it was longer on the left) were given a positive value, and leftward errors were given a negative value. By use of this rule, an pair of identical stimuli ($N = 0$) would yield a score of either +1 (if the 'rightward' key was pressed) or −1 (if the 'leftward' key was pressed); the size of the error recorded increased with the difference between the stimuli. A total net error score was calculated in this way for each stimulus series for each subject. This scoring procedure was performed separately for the longer/larger instruction and for the shorter/smaller instruction, giving two independent error scores for each stimulus dimension tested. These two opposite measures of perceptual bias were then averaged.

Subjects

Patients with visuospatial neglect: three were studied in this experiment.

MJ was a 61-year-old woman who had sustained a right hemisphere stroke 8 months prior to testing. A computer tomography (CT) scan performed 10 days post-onset showed a patchy low attenuation in the right mid/anterior white matter. The patient had a left hemiplegia and also a left homonymous hemianopia. Her score on the formal subtests of the Behavioural Inattention Test (BIT) [16] was 30 out of 146, with 100 % omissions in contralesional and central space in all cancellation tasks; in fact, only stimuli on the extreme right of the page were attended to.

BN was a 51-year-old man who had suffered from a right hemisphere stroke 7 months prior to testing. A CT scan performed 14 days post-onset showed a large fronto-parietal lesion. The patient had a left hemiplegia but no reported hemianopia. His BIT score was 51/146 with 100 % omissions in contralesional and central space in all cancellation tasks; again only stimuli on the extreme right of the page were attended to.

JW was a 63-year-old man who had sustained a right hemisphere stroke 5 months prior to testing. A CT scan performed 12 days post-onset showed an infarct in the right temporo-parietal region. The patient had a left hemiplegia and also a left homonymous hemianopia. His BIT score was 126/146, his omissions occurring in contralesional space only.

Brain-damaged controls: twelve patients with unilateral right hemisphere infarct (mean age 65.8 years, SD 6.2 years; six male, six female) and 12 patients with unilateral left hemisphere infarct (mean age 58.4 years, SD 12.3 years; six male, six female) were tested. All of these patients had suffered cerebrovascular accidents (CVAs) within the previous 20 months, and none betrayed any evidence of hemispatial neglect at the time of testing. Two patients had shown signs of neglect acutely, but had fully recovered. CT scans were available on all of the patients, and none of them revealed any signs of bilateral damage. The two brain-damaged control groups did not differ significantly in the prevalence of hemianopia or hemiplegia, nor in the time elapsed between onset of illness and testing (mean right-CVA 9.5 months before testing, SD 5.3 months; mean left-CVA 12.1 months before testing, SD 6.4 months). The distribution of lesion locations was similar in the two groups, with all patients having at least some involvement either of the parietal lobe, frontal lobe, or subcortical structures, with the exception of one left-CVA patient, whose damage appeared to be restricted to the temporal lobe.

Healthy control subjects: twelve healthy subjects (mean age 66.2 years, SD 3.8 years; four male, eight female) were recruited from among patients' spouses and friends, and were reasonably well matched on age and on socioeconomic and educational criteria. None had any notable medical, neurological or psychiatric history.

Neuropsychological testing

The neglect patients scored significantly below the means of either the right-CVA ($t(13) = 2.40$, $p < 0.05$) or left-CVA controls ($t(13) = 2.60$, $p < 0.05$) on the formal subtests of the BIT [16]. The three neglect patients showed normal scores on the New Adult Reading Test [17] (IQs of 110, 105 and 98), and on three verbal subtests (Information, Vocabulary and Digit Span) of the Revised WAIS [18] (mean scores 10, 10 and 8). None showed any evidence of aphasia on the Very Short Minnesota Aphasia Test [19]. All three patients, however, fell within the 'impaired' range on the Benton Visual Form Discrimination Test [20], differing significantly from both the right-CVA ($t(13) = 2.98$, $p < 0.05$) and left-CVA ($t(13) = 2.84$, $p < 0.05$) control groups. This deficit is probably due largely to the fact that they rarely chose left-side stimuli in this multiple choice task. Neglect of left-field stimuli may also account for the fact that the three neglect patients scored well below average (means of 5, 5 and 6) on three WAIS performance subtests (Picture Completion, Block Design and Object Assembly) — significantly less well than their right-CVA ($t(13) = 4.62$, $p < 0.001$) or left-CVA ($t(13) = 6.96$, $p < 0.001$) counterparts.

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