Causes of cross-over in unilateral neglect: between-group comparisons, within-patient dissociations and eye movements

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Summary

Patients with left unilateral neglect bisect long horizontal lines to the right of the true centre. However, when given short lines, many of the same patients mark the midpoint to the left of the true centre, towards the otherwise neglected space. This paradoxical phenomenon has been termed ‘cross-over’ and is difficult to explain based on current accounts of the neglect syndrome. To explore the causes of cross-over, in a first study we evaluated bisection of 20, 100 and 200 mm horizontal lines in groups of unilateral brain-damaged patients with neglect and hemianopia, with neglect and no hemianopia, with hemianopia and no neglect and without neglect or hemianopia. Cross-over of 20 mm lines was found only in neglect patients with hemianopia. To ascertain further the influence of visual field defects on cross-over, in a second study we compared the performance of two right-brain-damaged patients with contralesional neglect and inferior quadrantanopia with that of a patient with inferior quadrantanopia and no neglect. Patients bisected lines oriented so as to cross or uncross the blind quadrant of the visual field. When short 20 mm lines crossed the blind quadrant, neglect patients showed cross-over; when the same lines crossed the seeing quadrants cross-over was absent. These findings were confirmed by the examination of a neglect patient with sparing of the central 5° of the contralesional left visual hemifield in the right eye and no sparing in the left eye. In monocular viewing, cross-over was present when 20 mm lines were bisected with the left eye and absent when bisected with the right eye. Recording of eye movements showed that at the moment of bisection left eye fixations shifted towards the contralesional line endpoint whereas right eye fixations remained anchored to the centre of the line. With long lines, both eyes deviated ipsilesionally. These results show that in neglect patients ipsilesional deviation in the bisection of long lines turns into apparently paradoxical contralesional bisection of short ones only when these cross a retinotopically blind sector of the neglected space. Cross-over seems to depend on the small spatial effects produced by reflexive contralesional gaze shifts allowing eccentric fixations with the seeing hemifield. During the bisection of long lines, these effects are cancelled out by the strong attentional deviation induced by the marked extension of the ipsilesional line segment. This explanation establishes coherence between cross-over and current accounts of the neglect syndrome.

Keywords: visual half-field; unilateral neglect; line bisection; eye movement; crossover effect


Introduction

The line bisection task, in which patients are required to mark with a pen the subjective midpoint of horizontal lines, is a time-honoured and widely used neuropsychological test that has proved sensitive to purely visual retinotopic disorders such as hemianopia and to higher order spatial disorders such as unilateral neglect (Behrmann et al., 2002). Patients with hemianopia due to unilateral damage in visual pathways up to the primary cortex typically try to compensate for their visual field defect by bisecting horizontal lines in the direction of the blind hemifield; that is, contralesionally to the objective line midpoint (Zihl and von Cramon, 1986; Kerkhoff, 1993; Barton and Black, 1998). Different from hemianopics, right-brain-damaged patients with unilateral neglect suffer from defective awareness and orienting to
stimuli or part of stimuli in the left contralesional space (Vallar, 1998; Bartolomeo and Chokron, 2002) and typically shift the subjective midpoint of long horizontal lines to the right of the objective one; that is, ipsilesionally (Schenkenberg et al., 1980; Binder et al., 1992; Doricchi and Angelelli, 1999). Importantly, extensive evidence from the work of different authors shows that this shift is more marked in neglect patients with damage in the posterior rather than middle cerebral artery territory (Binder et al., 1992; Doricchi and Angelelli, 1999; Azouvi et al., 2002) and in neglect patients with rather than without contralesional hemianopia (D’Erme et al., 1987; Binder et al., 1992; Harvey et al., 1995a; Bartolomeo and Chokron, 1999; Harvey and Milner, 1999; Daini et al., 2001, 2002; Doricchi and Angelelli, 1999; Doricchi et al., 2002a, b, 2003; Savazzi et al., 2004). This latter finding emphasizes that functional disruption of retinotopic representations of space aggravates the ipsilesional attentional bias suffered by neglect patients as a consequence of damage to multimodal representations of space in the parietal–frontal cortical areas and the white matter fibre bundles connecting these areas (Heilman and Valenstein, 1972; Mesulam, 1981; Vallar and Perani, 1986; Husain and Kennard, 1996; Gaffan and Hornak, 1997; Leibovitch et al., 1998; Mort et al., 2003; Doricchi and Tomaiuolo, 2003; Buxbaum et al., 2004).

Paradoxically, neglect patients frequently bisect short horizontal lines (i.e. 2–2.5 cm) to the left of the objective midpoint; that is, contralesionally, crossing over towards the otherwise neglected space (Marshall and Halligan, 1989; Chatterjee, 1995; Monaghan and Shillcock, 1998). This finding intrigues neurologists and neuropsychologists since it is in striking contrast with all of the current accounts of the neglect syndrome. In fact, cross-over can be hardly explained by defective representation or attention for the contralesional space (Bisiach and Luzzatti, 1978; Mesulam, 1981; Heilman et al., 1987), hyperattention for the ipsilesional space (Kinsbourne, 1987) or defective attentional disengagement from the ipsilesional space (Posner et al., 1982, 1984), or by hypothesizing that the contralesional sector of the line is subjectively perceived as if it was topologically compressed (Milner et al., 1993; Bisiach et al., 1994). All of these proposals predict ipsilesional rather than contralesional deviation in line bisection. This incongruity was tentatively accounted for by hypothesizing that the negligible extension of the ipsilesional side of short lines limits the pathological ipsilesional attentional bias of neglect patients, making it possible to redirect attention contralesionally (Monaghan and Shillcock, 1998). However, the mechanism causing cross-over through a still paradoxical redirection of attention in the contralesional direction remains elusive. This has been identified as possibly relating to various factors. Marshall and Halligan (1989) specifically argued that the sector of the line where neglect patients can place the subjective midpoint without noticing that the lengths of the two segments at its sides are different is abnormally enlarged (this sector is called ‘the zone of indifference’). The same authors further hypothesized that short lines might trigger the preferential ocular scanning of the contralesional side of the line. In this case, neglect patients might concentrate ocular fixations around the contralesional boundary of the zone of indifference and this would consequently induce cross-over. Tegner and Levander (1991) tentatively identified the contralesional pushing mechanism in the disinhibited perceptual completion of short lines. This account was based on the subjective report of one neglect patient showing cross-over who stated that short lines seemed to have a leftward greyish elongation. Chatterjee (1995) offered the first, more comprehensive account of cross-over. This author emphasized that effective distribution of spatial attention requires simultaneous enhancement of neural activity related to behaviourally relevant spatial information and inhibition of activity related to irrelevant information. Brain damage is likely to disrupt both of these excitatory and inhibitory mechanisms. According to this view, neglect patients bisect long lines ipsilesionally because of defective excitatory representation of the most contralesional section of the line in the damaged right hemisphere. Conversely, short lines disclose the clinical expression of defective inhibitory mechanisms in the same hemisphere, leading to confabulatory extension of the contralesional end of the line and paradoxical contralesional shift of its subjective midpoint. Monaghan and Shillcock (1998) modelled the hypotheses advanced by Chatterjee (1995) and showed that a right-skewed representation of horizontal segments in the intact left hemisphere combined with a less powerful and noised left-skewed representation in the damaged right hemisphere satisfactorily simulates ipsilesional bisection of long lines and contralesional bisection of short ones. More recently, Chatterjee and co-workers (2000) also described two right-brain-damaged patients who judged contralesional weights as lighter than ipsilesional weights, except for light weights, for which they crossed over and judged the contralesional weights as heavier. These authors proposed that cross-over could be a modality-independent phenomenon; however, the relationship between cross-over in the judgement of weights and cross-over in line bisection was not investigated in their study, which makes their original proposal still very preliminary. Finally, Ishiai et al. (2004) indicated that cross-over disappears when the deviation of the subjective centre of the line is measured with respect to the centre of the memorized extension of the line, and proposed that cross-over depends on representational overextension of the contralesional side of short lines. Notwithstanding these considerable theoretical efforts (for a previous excellent review see Monaghan and Shillcock, 1998), the incidence of cross-over in line bisection has never been systematically explored in the population of patients affected by unilateral neglect. This seems relevant for gathering clues about the cross-over paradox in the context of the different explanations of the neglect syndrome. A more systematic reinvestigation of the functional correlates of cross-over could start from the broad hypothesis that, independently of its true origin, contralesional redirection of attention...
inducing cross-over is less likely to be triggered in neglect patients with hemianopia than in those without visual field defects, as in the former the ipsilesional deviation in the line bisection test is generally more severe. Here, in a first study we tested this conjecture and evaluated the occurrence and magnitude of cross-over in groups of neglect patients with or without complete concomitant hemianopia. The performance of these two groups was compared with that of patients with pure hemianopia and of patients without neglect or hemianopia. This served, in particular, to verify whether cross-over in neglect patients is quantitatively comparable to the compensatory contralesional deviation usually found in hemianopic patients without neglect.

**First study: group comparisons**

**Method**

**Patients**

On admission to the rehabilitation hospital, patients were consecutively screened for inclusion in the study. Patients with bilateral strokes or signs of dementia were excluded. Four groups of patients were studied: seven right-brain-damaged patients with left unilateral neglect and complete left homonymous hemianopia with no macular sparing (N+H+); 12 right-brain-damaged patients with left unilateral neglect and no concomitant visual field defect (N+H–); six unilateral brain-damaged patients with complete contralesional homonymous hemianopia and no neglect (N–H+; four left-brain-damaged and two right-brain-damaged); and nine right-brain-damaged patients without neglect or hemianopia (N–H–). All patients had CT or MRI documentation.

All patients gave their informed consent to participation in the study. Clinical and demographic data are summarized in Table 1. The visual field was tested by Goldman kinetic perimetry. In all N+H+ patients hemianopia was also present on clinical confrontation testing.

**Clinical assessment of neglect**

Unilateral neglect was assessed with a standardized battery (Pizzamiglio et al., 1989) composed of four tests.

(a) **Line cancellation** (Albert, 1973): the score is the number of short line segments cancelled on a horizontally oriented sheet of A3 paper (total score range 0–21; 0–11 on the left, 0–10 on the right). Segments are arranged in scattered order and random orientation on the sheet of paper.

(b) **Letter cancellation** (Diller et al., 1974): the score is the number of target capital letters cancelled on a horizontally oriented sheet of A3 paper (total score range 0–104; 0–53 on the left, 0–51 on the right). Letters are arranged in six rows. In each row, target letters (H) are intermixed with filler letters.

(c) **Wundt–Jastrow area illusion test** (Massironi et al., 1988): the score is the frequency of perception of the optical illusion when the two fans are oriented towards the contralesional or the ipsilesional side of space (score range 0–20).

(d) **Sentence reading test** (Pizzamiglio et al., 1992): the score is the number of sentences read without omissions (score range 0–6).

Higher scores indicate better performance on tests a, b, d and worse performance on test c.

**Experimental procedure**

**Line bisection task.** Patients were required to bisect black horizontal lines that were 20, 100 and 200 mm in length and 2.5 mm in thickness. Lines were presented on a table, each centred on a horizontally oriented sheet of A4 white paper. The centre of all the lines was aligned to the patient’s head–body midsagittal plane. Patients performed the task in free vision and were instructed not to cover task stimuli with the right hand holding the pencil. Five trials were

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Age (years)</th>
<th>Stroke onset (days)</th>
<th>Line cancellation</th>
<th>Letter cancellation</th>
<th>Wundt–Jastrow</th>
<th>Sentence reading</th>
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<tr>
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<td></td>
<td>Right (10)</td>
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<tr>
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<td>5.86</td>
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<td>6.63</td>
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<td>82.93</td>
<td>0.33</td>
<td>6.25</td>
<td>0.00</td>
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</table>

N–H– = patients without neglect or hemianopia; N–H+ = patients with hemianopia and no neglect; N+H– = patients with neglect and no hemianopia; N+H+ = patients with neglect and hemianopia. Maximum scores on paper/pencil cancellation tasks are indicated in italics at the tops of corresponding columns.
administered for each line length. Lines of each length were presented in separate blocks of trials. This was done to avoid context effects among lines of different lengths (i.e. length underestimation of lines preceded by longer ones or length overestimation of lines preceded by shorter ones) (Marshall et al., 1998). Blocks were administered in random order. A distracting pause lasting 5–10 min was interpolated between consecutive blocks of trials. Short 20 mm lines were used, because cross-over is most homogeneously observed with lines shorter than 40 mm (Monaghan and Shillcock, 1998; Ricci and Chatterjee, 2001).

**Midpoint of subjective 20 mm line length (testing confabulatory extension of the line).** Following Chatterjee’s suggestion (1995), we were able to assess the possible influence of confabulatory perceptual extension of the contralesional side of short lines on cross-over in three N+H+ (cases a, b and c; Table 3 and Fig. 2) and three N+H– patients (cases d, e and f; Table 3 and Fig. 2). In these patients, we evaluated subjective midpoint position, taking as reference the midpoint of subjective rather than objective line length. This was done in a separate session by asking patients to bisect five additional 20 mm lines and mark their endpoints. This allowed comparison between deviation of bisection from the objective midpoint of the line and deviation of bisection from the midpoint between the endpoints marked by patients on the printed line (i.e. subjective midpoint). This task should not be confounded with the endpoint task (Bisiach et al., 1994; Doricchi and Angelelli, 1999), in which the length of a line or of a horizontal distance is reproduced by setting its endpoints with no line or distance printed where the endpoints have to be marked.

**Results**

**Clinical data**

Group means with standard deviations are reported in Table 1. Groups did not differ for age or time elapsed from stroke onset [\(F(<1 \text{ in both cases})\)].

**Neglect tests**

**Line cancellation.** A group (N+H+, N+H–, N–H+, N–H–) \(\times\) side (contralateral, ipsilateral) ANOVA revealed a significant group effect [\(F(3,30) = 6, P < 0.01\)] and group \(\times\) side interaction [\(F(3,30) = 4.8, P < 0.01\)]. Planned comparisons showed that both N+H+ and N+H– cancelled fewer contralesionally than ipsilaterally items (all \(P < 0.001\)) and cancelled fewer items than any other group on both sides of space (all \(P < 0.001\)). On the left side, N+H+ cancelled fewer items than N+H– (\(P < 0.01\)). No side difference or between-group differences were found between N–H+ and N–H– groups.

**Letter cancellation.** A group (N+H+, N+H–, N–H+, N–H–) \(\times\) side (contralateral, ipsilateral) ANOVA revealed significant group [\(F(3,30) = 25, P < 0.001\)], side [\(F(1,30) = 29, P < 0.001\)] and group \(\times\) side interaction [\(F(3,30) = 17, P < 0.001\)]. Planned comparisons showed that both N+H+ and N+H– cancelled fewer contralesionally than ipsilaterally items (all \(P < 0.001\) and cancelled fewer items than any other group on both sides of space (all \(P < 0.001\)). No significant difference was found between N+H+ and N+H– groups. No side difference or between-group differences were found between N–H+ and N–H– groups.

**Wundt–Jastrow area illusion test.** Individual frequencies of missed perception of the visual illusion were submitted to a group (N+H+, N+H–, N–H+, N–H–) \(\times\) stimulus orientation (leftward, rightward) ANOVA. There were significant group [\(F(3,30) = 12, P < 0.001\)], orientation [\(F(1,30) = 59, P < 0.001\)] and group \(\times\) orientation interactions [\(F(3,30) = 24, P < 0.001\)]. Planned comparisons showed that both N+H+ and N+H– missed the illusion more frequently when the fans were oriented leftwards than all of the other groups (all \(P < 0.001\)). However, misses for leftward-oriented stimuli were more frequent in N+H+ than N+H– (all \(P < 0.001\)). No difference was found among groups for rightward oriented stimuli.

**Sentence reading.** The number of sentences read without omissions varied among the groups of patients [\(F(3,30) = 21, P < 0.001\)]. Both N+H+ and N+H– patients made more omissions than the other two groups (planned comparison, \(P < 0.01\) in both cases). However, N+H+ made more omissions than N+H– (\(P < 0.01\)).

**Experimental data**

**Line bisection task.** Averaged individual percentage deviations of the subjective from the objective midpoint of lines were submitted to angular transformation and entered in a group (N+H+, N+H–, N–H+, N–H–) \(\times\) line length (200 mm, 100 mm, 20 mm) ANOVA. Both main effects and their interaction were significant [group, \(F(3,30) = 7, P < 0.001\); line length, \(F(2,60) = 124, P < 0.0001\); group \(\times\) line length, \(F(6,60) = 35, P < 0.0001\)]. Planned comparisons showed that, with 200 mm lines, N+H+ bisected more ipsilaterally than all of the other groups (\(P < 0.001\)) and that N+H– bisected more ipsilaterally than N–H+ and N–H– groups (\(P < 0.001\)). No difference was found between these two latter groups. The pattern of results with 100 mm lines was identical to that found with 200 mm ones. With 20 mm lines, N+H+ had dramatic directional reversal in their performance showing contralesional rather than ipsilaterally deviation. This deviation was significantly higher than the contralesional compensatory deviation of N+H+ patients (\(P = 0.001\)). The deviations of N+H+ and N+H– groups were both significantly different from the perfect performance of N+H– and N–H– groups (\(P < 0.001\) in both cases).

Percentage deviations are reported in Fig. 1, raw deviations (with SD) in Table 2. Individual raw deviations in the bisection of 20 mm lines are depicted in Fig. 2.

**Midpoint of subjective 20 mm line length.** Averaged individual deviation of bisection from the midpoint of objective 20 mm line length was compared with averaged deviation...
N+H+ = patients with neglect and hemianopia.
N+H– = patients with neglect and no hemianopia;
N–H– = patients without neglect or hemianopia;
N–H+ = patients with hemianopia and no neglect; N+H– = patients with neglect and no hemianopia; N+H+ = patients with neglect and hemianopia.

Fig. 1 First study: averaged percentage deviations of the subjective line midpoint (at line lengths 20 mm, 100 mm, 200 mm) in each group. Positive values indicate ipsilesional deviation from the objective midpoint; negative values indicate contralesional deviation. N–H– = patients without neglect or hemianopia; N–H+ = patients with hemianopia and no neglect; N+H– = patients with neglect and no hemianopia; N+H+ = patients with neglect and hemianopia.

Table 2 First study: averaged group deviations (mm) and SD of subjective line midpoint at line lengths 20, 100 and 200 mm

<table>
<thead>
<tr>
<th>Group</th>
<th>Line length</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>20 mm %</td>
</tr>
<tr>
<td>SD</td>
<td>1.2</td>
</tr>
<tr>
<td>N+H–</td>
<td>+0.02</td>
</tr>
<tr>
<td>SD</td>
<td>1.19</td>
</tr>
<tr>
<td>N–H+</td>
<td>-0.9</td>
</tr>
<tr>
<td>SD</td>
<td>0.68</td>
</tr>
<tr>
<td>N–H–</td>
<td>-0.006</td>
</tr>
<tr>
<td>SD</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Positive values indicate ipsilesional deviation from the objective midpoint. Negative values indicate contralesional deviation.

from the midpoint of the subjective 20 mm line length (i.e. the distance between the subjective line endpoints) through a group (N+H+, N+H–) × line length representation (objective, subjective) ANOVA. A significant group effect was found \([F(1,4) = 10, P = 0.03]\) with no significant line length representation effect or group \(×\) line length representation interaction. No noticeable confabulatory extension of the contralesional side of 20 mm lines was found in neglect patients. In N+H+ patients, cross-over was still present when the position of the subjective midpoint was recalculated with respect to the perceived length of 20 mm lines. Planned comparisons showed that, regardless of objective or subjective line length, N+H+ patients bisected contralesionally (bisection of objective length = –3.3 mm, bisection of subjective length = –3.25) compared with N+H– patients (bisection of objective length = +1 mm, bisection of subjective length = +0.95 mm; \(P < 0.001\) in all cases). No group showed significant modification of bisection performance as a function of objective or subjective line length (not significant in all cases). Individual subjective midpoint position, subjective left and right line endpoints and the midpoint of perceived line length are reported in Table 3. Deviations from the objective midpoint of 100 and 200 mm lines are also reported.

Lesion site in N+H+ patients. To clarify whether cross-over can occur in both posterior cerebral artery (PCA) and middle cerebral artery (MCA) neglect patients who also have a field defect, we examined the localization of brain damage in each of the N+H+ patients. Images or clinical reports of individual lesions (Fig. 3) show that in this group there were the following subgroups of patients. (i) Six patients (cases 1–6) had an extended parietal–temporal–frontal cortical–subcortical lesion (MCA lesion). In this subgroup, radiological images were available for four patients (cases 1–4). In these cases hemianopia seemed to depend on damage of areas irrigated by the perforating branches of the MCA: the posterior thalamic area and/or the optic radiations immediately behind the geniculate body, just posterior to the retro lenticular sector of the internal capsule. In case 2, hemianopia could have also depended on haemorrhagic lesion of the optic tract. (ii) One patient (case 7) had an extended lesion of the optic radiations in the parietal–occipital white matter (PCA territory). These data might suggest that cross-over in neglect patients with complete hemianopia is independent of the localization of the brain damage causing the visual field defect.

Discussion

The results of this group study show that cross-over with short horizontal lines is present in patients with neglect and complete hemianopia and absent in patients with neglect and no hemianopia. These findings disclose regularity in the appearance of cross-over, suggesting that it can no longer be considered a bizarre phenomenon emerging occasionally in the neglect patient population. Interestingly, cross-over in patients with neglect and hemianopia was stronger than the compensatory contralesional deviation shown by pure hemianopic patients in the bisection of short lines. This finding does not seem spuriously influenced by the presence of patients with left brain damage in the hemianopic group since in this type of patient the side of the visual
field defect has no influence on the evaluation of contra-
lesional horizontal distances (Zihl and von Cramon, 1986). In
three of the neglect patients considered in this study, we
tested the subjective length of 20 mm lines and found no
length misperception. This suggests that cross-over can be
dissociated from confabulatory extension of the contra-
lesional side of short lines (Chatterjee, 1995; Tegner and

Fig. 2 First study: scatter-plot of individual deviations (in mm) in the bisection of 20 mm lines. Data are plotted separately for each
experimental group. Positive values indicate ipsilesional deviation; negative values indicate contralesional deviation. Right-brain-damaged
patients are indicated by empty circles and N–H+ patients (i.e., pure hemianopics) with left brain damage by filled circles. The group
mean is indicated by a vertical line, with its corresponding value (in mm) reported at the top of the line. Neglect patients in which
the subjective length of 20 mm lines was evaluated are indicated by a lowercase letter. Detailed performances of these patients in the line
bisection and endpoint setting tasks are reported in Table 3.

Table 3 First study: individual averaged deviations of three N+H+ (cases a, b and c) and three N+H– patients
(cases d, e and f; see also Fig. 2) in the bisection of the objective length of 200, 100 and 20 mm lines and in the bisection
of the subjective length of 20 mm lines

<table>
<thead>
<tr>
<th>Group</th>
<th>Case in Fig. 2</th>
<th>Objective line length (mm)</th>
<th>Subjective line length</th>
<th>Left endpoint</th>
<th>Right endpoint</th>
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<tr>
<td></td>
<td></td>
<td>200</td>
<td>100</td>
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</tr>
<tr>
<td>N+H+</td>
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<td>+32.60</td>
<td>+3.00</td>
<td>+2.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.24</td>
<td>9.49</td>
<td>2.15</td>
<td>2.15</td>
</tr>
<tr>
<td>N+H–</td>
<td>f</td>
<td>+26.90</td>
<td>+8.10</td>
<td>-0.50</td>
<td>+0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.83</td>
<td>2.51</td>
<td>0.78</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Positive values indicate ipsilesional deviation from the objective midpoint. Negative values indicate contralesional deviation. Endpoint
setting of 20 mm lines: positive values = endpoint positioned outside the end of the line; negative values = endpoint positioned
inside the line.
The selective presence of cross-over in neglect patients with concomitant hemianopia countered the expectation that the redirection of attention towards the contralesional side of short lines would be more readily observed in neglect patients without hemianopia who, like similar patients in most previous studies, had smaller ipsilesional deviation in the bisection of long lines. Though apparently counterintuitive, the prevalence of cross-over in neglect patients with concomitant visual field defects is consonant with unrecognized findings from most studies investigating the bisection of short lines (2–2.5 cm). The two neglect patients studied by Halligan and Marshall (1988; 2.5 cm lines) and the one by Anderson (1997; 1 cm and 2 cm lines) were all hemianopic and showed clear cross-over. Most importantly, of the two patients reported in another study by Halligan and Marshall (1989), the one showing consistent cross-over with 2.5 cm lines was the hemianopic one (PS), whereas the performance of the non-hemianopic patient (JH) was close to that of healthy controls. Also, among the five patients examined by Chatterjee (1995), the only two patients who showed cross-over in the bisection of 2 cm lines (Fig. 2 in Chatterjee, 1995) were those with hemianopia (SP and MJT). The three remaining patients from the same study (MS with inferior quadrantanopia, RM and FJ without visual field defects) showed no evidence of cross-over. Of the seven patients with sensory neglect studied by Harvey et al. (1995b), the only one showing no cross-over with 2.5 cm lines was the only one suffering no hemianopia (case IH). More recently, Ishiai et al. (2004) found cross-over of 2.5 cm lines in two patients with neglect and hemianopia and in one with neglect and inferior quadrantanopia. With slightly longer lines (4 cm or more), contralesional bias in bisection appears even more frequently in neglect patients with hemianopia (the case reported by Anderson, 1997; four of the seven patients with neglect and hemianopia examined by Ricci and Chatterjee, 2001: patients LAB, JF, CC and MT) and is never present in patients with neglect and no visual field defects (all three patients studied by Ricci and Chatterjee, 2001: patients EB, LB and BH). As regards group studies, Mennemeier et al. (2001) found no difference in the bisection of 2 cm lines in normal controls and in a group of right-brain-damaged patients with neglect in which fewer than 10% of patients suffered from visual field defects. Compared with this ample and coherent series of data from studies of different authors, the only discrepant observation is reported by Tegner and Levander (1991), who found cross-over of 2.5 cm lines in four neglect patients without visual field defects (out of the 25 patients considered in their study). In this latter study,

Fig. 3 First study: individual radiological images and reports of N+H+ patients (cases 1–7).
however, the method used to assess the visual field defect was not specified.

Discrepant findings from studies investigating the neglect syndrome may be due to differences in relevant methodological variables, such as: (i) the method used to assess concomitant visual field defects (clinical confrontation testing versus static or dynamic ophthalmological perimetric testing; for review see Halligan and Marshall, 2002; Russel et al., 2004); for example, with very short lines even a small area of sparing around the fovea, remaining undetected on clinical confrontation testing, might significantly affect the bisection of short lines and the appearance of cross-over; (ii) the task used for neglect evaluation (line bisection versus cancellation or drawing tasks), as different tasks might tap different spatial abilities (Binder et al., 1992; Doricchi and Angelelli, 1999; Azouvi et al., 2002); (iii) the time elapsed between the diagnosis of neglect at stroke onset and the experimental testing of patients, as it is well established that neglect symptoms may significantly change or even disappear in the subacute and chronic phase of illness (Stone et al., 1992).

To further and better assess the influence of visual field defects on cross-over, all of these limitations can be circumvented by studying neglect patients with cerebral blindness limited to one quadrant of their contralesional visual field and by comparing in each patient the bisection of lines aligned to the directions of the frontal–parallel plane crossing the blind quadrant with the bisection of lines uncrossing the same quadrant (Doricchi et al., 2003).

Here, in a second study we contrasted the line bisection performance of two right-brain-damaged patients with contralesional neglect and inferior quadrantopia (NQ1 and NQ2) with that of a right-brain-damaged patient with an analogous visual field defect and no neglect (Q). In each patient, the influence of visual field defects on line bisection was examined by imposing three different orientations on the lines to be bisected: horizontal, 45° clockwise (CW) and 45° counterclockwise (CCW). Lines were presented with their centre aligned to the midsagittal plane of the patient’s body. In this way, depending on line orientation, the contralesional section of the line could either cross or uncross the retinotopically blind quadrant, making it necessary for the patient (inspecting the line in free vision) to compensate or not for the field defect. Importantly, in one of the neglect patients the field defect extended to the inferior third of the upper contralesional quadrant, therefore including the entire extent of the contralesional horizontal meridian. This allowed us to make additional within and between comparisons of the two neglect patients’ performances. With this investigative design, we were able to compare the influence of different spatial associations and dissociations of attentional neglect and visual field defects in the bisection of 20, 100 and 200 mm lines. At the end of the experimental session, the possible influence of perceptual completion (i.e. subjective extension) of the contralesional side of the line on cross-over was investigated by asking the two neglect patients to mark the subjective left and right endpoints of 20 mm lines. Bisection deviations were then recalculated with respect to the centre of the distance between the subjective endpoint positions (i.e. the subjectively perceived line length) and recompared with the performance of the patient without neglect.

Second study: within-patient dissociations

Patients

NQ1 is a 65-year-old right-handed man. In February 2002 he sustained a cortical and subcortical stroke in the temporal–frontal–parietal area of the right hemisphere. The stroke resulted in left hemiplegia. At the moment of testing, 54 days later, intellectual functions were within the normal range, with no memory or language impairment. Kinetic Goldman perimetry indicated left inferior quadrantopia without macular sparing. The visual field defect extended to the inferior third of the upper left quadrant. Severe left-side extrapersonal neglect was found.

NQ2 is a 54-year-old right-handed man. In June 2003 he sustained a right frontal–parietal–temporal stroke with involvement of the basal ganglia, the semioval centre and the corona radiata. A neuropsychological examination, made 100 days after the stroke, revealed the presence of mild left-side extrapersonal neglect (although in the line bisection task his neglect was relatively more severe than that of NQ1). General intellectual functions were within the normal range, with no memory or language impairment. Kinetic Goldman perimetry disclosed left inferior quadrantopia without macular sparing.

Q is a 75-year-old right-handed man. In May 2002 he sustained a right cerebral stroke. The damage involved the precuneus, the cuneus, the superior calcarine area in the medial aspect of the hemisphere and the superior occipital gyrus on the lateral aspect of the same hemisphere. A neuropsychological examination, made 117 days after the stroke, showed normal intellectual functions with no memory or language impairment. Q had no signs of contralesional neglect. Humphrey’s static perimetry revealed left inferior quadrantopia without macular sparing.

Clinical and demographic data are summarized in Table 4. Visual perimetrics are reported in Fig. 4. Radiological images are shown in Fig. 5. The localization of the lesion was defined according to Duvernoy’s (1991) anatomical atlas.

Methods

Clinical assessment of neglect

Neglect was assessed with the standardized battery used in the first study (Pizzamiglio et al., 1989).

Experimental procedure

Line bisection task. Patients were required to bisect black 20, 100 and 200 mm lines. Lines were presented individually, each centred on a horizontally placed sheet of A4 white paper.
The orientation of the line on the sheet could be horizontal, clockwise (CW, i.e. sloping 45° to the right) or counterclockwise (CCW, i.e. leaning 45° to the left). Lines of each length were presented in separate blocks of trials. Blocks were administered in random order in separate daily experimental sessions. Each block consisted of 30 trials, 10 for each orientation (horizontal, CW and CCW). In each block, the line orientation was randomly varied across trials. Control ranges (95% confidence interval: mean ± 2 SEs; Figs 5, 6 and 8) of bisection performance in the different length and orientation conditions were obtained from the N–H– group included in the first study (see clinical and bisection data in Table 4 and Fig. 6).

Midpoint of subjective 20 mm line length (testing confabulatory extension of the line). Immediately after they had bisected 20 mm lines, neglect patients were required to mark with a pencil the endpoints of additional 20 mm horizontal, CW and CCW lines. Stimulus presentation was analogous to that of the bisection task. Five trials were administered for each line orientation. Line orientation was randomly varied across trials. To assess the influence of confabulatory perceptual completion (i.e. extension) of the contralateral side of short lines on cross-over, percentage deviations from each of the 20 mm bisection trials performed by the two neglect patients were recalculated, taking as reference the midpoint of subjective line length. Subjective line length was evaluated by measuring the distance between the averaged position of the endpoints marked by NQ1 and NQ2 on the printed 20 mm lines. This task should not be confounded with the endpoint task (Bisiach et al., 1994; Doricchi and Angelelli, 1999), in which endpoints have to be set with no printed line on the paper sheet.

Results

Line bisection task

Percentage deviations of the subjective from the objective midpoint of lines measured in each trial were submitted to angular transformation and entered in a patient (NQ1, NQ2, Q) × orientation (horizontal, CW, CCW) × line length (200 mm, 100 mm, 20 mm) ANOVA. Ipsilesional deviations were scored as positive values, contralateral deviations as negative values. In the general ANOVA, all simple effects and interactions were significant (P < 0.01). In the following section, we report the results of the separate ANOVAs comparing the patients’ individual line orientation performances (between-patients comparisons) and each patient’s different line orientation performances (within-patients comparisons). Percentage and raw midpoint deviations are reported in Fig. 6.

Between-patients comparisons

(patient × line length ANOVAs)

Horizontal (blind meridian in NQ1, seeing meridian in NQ2 and Q). Different percentage deviations were found among patients [F(2, 27) = 47.4, P < 0.01], among lengths [F(2, 54) = 54.4, P < 0.001] and among patients as a function of length [F(4, 36) = 18.7, P < 0.001]. With 200 mm lines, both NQ1 and NQ2 deviated ipsilesionally, while Q deviated contralaterally (both planned comparisons, P < 0.0001). No difference was present between NQ1 and NQ2. Although Q’s performance was perfect with 100 mm lines, cross-over in the contralateral direction was present in NQ1 (which can be accounted by between-patient variability in the presence of cross-over with lines of moderate length; Monaghan and Shilcock, 1998; Ricci and Chatterjee, 2001) and significant ipsilesional deviation in NQ2 (both comparisons, P < 0.0001). With 20 mm lines, NQ1 had much stronger contralateral deviation than both NQ2 and Q (both comparisons, P < 0.01); no difference was present in the performances of the two latter patients.

Clockwise (blind meridian in all patients). Different percentage deviations were found among patients [F(2, 27) = 21, P < 0.001], among lengths [F(2, 54) = 90, P < 0.001] and among patients as a function of length [F(2, 54) = 13.7, P < 0.001]. With 200 mm lines, NQ1 and NQ2 had similar ipsilesional deviation (not significant) compared with the contralateral deviation showed by Q (both planned comparisons, P < 0.0001). The same was found with 100 mm lines (both comparisons, P < 0.01). With 20 mm lines, the bisection deviations of both NQ1 and NQ2 showed a dramatic directional reversal, changing from ipsilesional to contralateral (i.e. cross-over along the contralaterally blind meridian). Importantly, these deviations were both significantly higher than the much smaller compensatory contralateral deviation showed by Q (both comparisons, P ≲ 0.02).

Counterclockwise (seeing meridian in all patients). Different percentage deviations were found among patients [F(2, 27) = 13.3, P < 0.001], among lengths [F(2, 54) = 80, P < 0.001] and among patients as a function of length [F(2, 54) = 11, P < 0.001]. With 200 mm lines, both NQ1

Table 4 Second study: individual demographic and clinical data of patients NQ1, NQ2 and Q

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Stroke onset (days)</th>
<th>Line cancellation Left (11)</th>
<th>Right (10)</th>
<th>Letter cancellation Left (53)</th>
<th>Right (51)</th>
<th>Wundt–Jastrow Left (0)</th>
<th>Right (0)</th>
<th>Line bisection (200 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NQ1</td>
<td>65</td>
<td>3/11</td>
<td>9/10</td>
<td>0/53</td>
<td>18/51</td>
<td>7/20</td>
<td>0/20</td>
<td>+7.2 mm</td>
</tr>
<tr>
<td>NQ2</td>
<td>54</td>
<td>8/11</td>
<td>10/10</td>
<td>48/53</td>
<td>51/51</td>
<td>12/20</td>
<td>0/20</td>
<td>+15 mm</td>
</tr>
<tr>
<td>Q</td>
<td>75</td>
<td>11/11</td>
<td>10/10</td>
<td>53/53</td>
<td>51/51</td>
<td>n.a.</td>
<td>n.a.</td>
<td>−3.3 mm</td>
</tr>
</tbody>
</table>

Maximum scores on paper/pencil cancellation tasks are indicated in italics at the tops of corresponding columns. n.a. = not administered.
and NQ2 deviated more ipsilesionally than Q (both comparisons, $P < 0.01$), NQ2 deviating more ipsilesionally than NQ1 ($P < 0.001$). With 100 mm lines, NQ2 deviated more ipsilesionally than both of the other two patients ($P < 0.001$), who bisected lines very close to the objective midpoint. With 20 mm lines, all patients showed comparable contralesional deviation (all comparisons not significant).

**Within-patient comparisons**

*orientation $\times$ line length ANOVAs*

NQ1 (blind meridians: horizontal and CW). Positioning of the subjective midpoint varied as a function of orientation [$F(2,18) = 14.2, P < 0.001$], length [$F(2,18) = 58, P < 0.0001$] and the interaction of both of these factors [$F(4,36) = 5.5, P < 0.01$]. With 200 mm lines, comparable ipsilesional

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**Fig. 4** Second study: visual perimeters of NQ1, NQ2 and Q patients (Goldman test stimulus: size III, intensity 4e).
deviations were found among the different line orientations (all planned comparisons, not significant). With 100 mm lines, cross-over was already present for horizontal lines but not for CW and CCW lines (100 mm versus 200 mm lines, horizontal $P < 0.001$; CW and CCW, not significant). With 20 mm lines, a significant increase in contralesional deviation (cross-over) was found for horizontal and CW lines crossing the blind sector of the visual field (20 mm versus 100 mm lines, horizontal and CW, $P < 0.02$) but not for CCW lines uncrossing the same sector (20 mm versus 100 mm lines, not significant). Horizontal and CW 20 mm lines crossing the retinotopically blind sector of the visual field were bisected more ipsilesionally than CCW lines uncrossing the blind sector (both comparisons, $P < 0.001$; horizontal versus CW, not significant).

$NQ2$ (blind meridian: CW). Positioning of the subjective midpoint varied as a function of orientation [$F(2,18) = 16.2$, $P < 0.001$], length [$F(2,18) = 351$, $P < 0.0001$] and the interaction of both of these factors [$F(4,36) = 3.5$, $P = 0.01$]. With 200 mm lines, ipsilesional deviation was significantly more severe for CCW lines crossing the blind area of the visual field than for both horizontal or CW lines uncrossing the same area ($P < 0.001$; horizontal versus CCW, not significant).

$Q$ (blind meridian: CW). Positioning of the subjective midpoint varied as a function of orientation [$F(2,18) = 7.9$, $P < 0.005$], length [$F(2,18) = 10.9$, $P < 0.001$] and the interaction of both of these factors [$F(4,36) = 6.2$, $P < 0.001$]. With 200 mm lines, comparable compensatory contralesional deviation was found at all line orientations (all planned comparisons not significant). With 100 mm lines, contralesional deviation became more marked for CW lines (100 mm versus 200 mm, $P < 0.01$) and turned into ipsilesional deviation for horizontal and CCW lines (100 mm versus 200 mm, $P = 0.01$). With 20 mm lines, contralesional deviation was found at all line orientations (20 mm versus 100 mm lines, horizontal $P < 0.01$, CCW $P < 0.001$, CW not significant).

Midpoint of subjective 20 mm line length (testing confabulatory extension of the line). Errors in endpoint localization were negligible (Table 5). Ipsilesional deviations were scored as positive values and contralesional deviations as negative ones (Fig. 7). Percentage deviations from each of the 20 mm bisection trials performed by the two neglect patients were recalculated, taking as reference the midpoint of the distance between averaged individual subjective endpoints. Corrected percentages of deviation from $NQ1$ and $NQ2$ were submitted to angular transformation and compared with $Q$‘s performance using a patient ($NQ1$, $NQ2$, $Q$) × orientation (horizontal, CW, CCW) ANOVA. The ANOVA [patient × orientation interaction, $F(4,54) = 5$, $P = 0.001$] confirmed higher contralesional deviation with horizontal lines in $NQ1$ than in $NQ2$ and $Q$ (both planned comparisons, $P < 0.001$), higher contralesional deviation with CW lines in $NQ1$ and $NQ2$ than in $Q$ (both planned comparisons, $P < 0.001$) and no difference among patients in the bisection of CCW lines (all planned comparisons not significant).

Discussion
The findings of this second study confirm the results of the first group study, suggesting that poor attentional attraction by the ipsilesional side of short lines is not the only factor determining cross-over, since cross-over was present only when short lines crossed the retinotopically blind area of the neglected space. Bisection of short lines crossing the seeing sectors of the visual field was comparable among patients with and without neglect. With long 200 mm lines, ipsilesional deviation was found at all line orientations only in neglect patients.
Fig. 6 Second study: line bisection task. Averaged percentage deviations from the objective line midpoint in the different orientation and line length conditions. Vertical bar at value 0 on the abscissa indicates perfect performance. Positive values indicate ipsilesional deviation; negative values indicate contralesional deviation. Numbers indicate raw means in mm with corresponding raw standard deviations in parentheses. Thin horizontal lines inside the graph represent the 95% confidence interval obtained from the N–H– sample considered in the first study.

Table 5 Second study: averaged localization of subjective line endpoints, with respect to objective ones, in the different line orientations in patients NQ1 and NQ2

<table>
<thead>
<tr>
<th></th>
<th>Horizontal</th>
<th>Clockwise</th>
<th>Anticlockwise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>NQ1</td>
<td>+0.5 (1)</td>
<td>0.00 (0.35)</td>
<td>−0.2 (0.27)</td>
</tr>
<tr>
<td>NQ2</td>
<td>+0.8 (0.45)</td>
<td>−0.2 (0.27)</td>
<td>+0.2 (0.27)</td>
</tr>
</tbody>
</table>

Positive values indicate overextension (i.e. endpoints are positioned outside the line); negative values indicate underextension (endpoints are positioned inside the line). Standard deviations are in parentheses. All values are in mm.
In this second study, severity of neglect in line bisection was unrelated to cross-over. On clinical examination, neglect was generally more severe in NQ1 than in NQ2, with the notable exception of the line bisection task, for which the ipsilesional deviation of NQ2 was twice that of NQ1 (Table 4). In the experimental task, ipsilesional deviation with 200 mm horizontal lines was comparable in these two patients (although NQ2 tended towards higher deviation). However, cross-over with 20 mm horizontal lines was present only in NQ1, in whom the horizontal meridian was comprised by the field defect. With 200 mm CW lines crossing the blind quadrant, NQ1 and NQ2 had similar neglect and both showed cross-over of 20 mm CW lines. Finally, with 200 mm CCW lines oriented across the spared upper contralesional quadrant, neglect was more severe in NQ2 than in NQ1. However, neither NQ1 nor NQ2 showed higher contralesional deviation than Q in the bisection of short CCW 20 mm lines. Importantly, in both neglect patients contralesional deviation in the bisection of CCW 20 mm lines crossing the seeing quadrant was significantly smaller than in the bisection of 20 mm lines crossing the blind sectors of their visual fields (horizontal and CW lines in NQ1, CW lines in NQ2).

As in the first study, when short 20 mm lines were oriented across the blind sectors of the visual field, the contralesional deviation shown by NQ patients was much higher than the compensatory deviation exhibited by patient Q (Zihl and von Cramon, 1986; Kerkhoff, 1993; Barton and Black, 1998). The overcompensation towards the neglected and blind contralesional space resembles the behaviour of acute hemianopics and patients suffering from both neglect and hemianopia. Acute hemianopics overshoot contralesional targets when learning to alternate ocular fixations between two lateral targets, one in the blind and one in the seeing hemifield (Meienberg et al., 1986). With practice, however, saccadic overshooting is progressively replaced by spatially calibrated saccades (Meienberg et al., 1986). Similarly, patients suffering from concomitant contralesional neglect and hemianopia overextend into the contralesional space distances presented in the ipsilesional one (Bisiach et al., 1994; Ishiai, 2002; Doricchi, 2002; Doricchi et al., 2003). This error is accompanied by saccadic and manual overshooting (Ishiai, 2002) and persists in the chronic phase (Doricchi and Angelelli, 1999). In agreement with previous investigators of cross-over, we speculate that short lines having no salient ipsilesional section might allow the distribution of ocular fixations to be shifted towards the side of the blind field. However, here we wish to propose that this might be specifically linked to reflexive contralesional ocular deviations enabling, as in the case of patients with central scotoma or hemianopia (Trauzettel-Klosinsky and Reinhard, 1998; Safran et al., 1999), the use of the so-called pseudofovea, an eccentric retinal locus of fixation located in the area of the seeing field adjacent to the blind sector of the fovea. To better clarify this proposal, some critical factors that might differentiate the bisection performances of pure hemianopic patients from those of patients suffering from both neglect and hemianopia can be considered. Patients with pure hemianopia (Zihl, 1995; Trauzettel-Klosinsky and Reinhard, 1998) actively counteract their visual field defect. We argue that during bisection, the contralesional reflexive pseudofoveal bias in these patients is also accompanied by active compensatory inspection of the contralesional sector of the line (Ishiai et al., 1987; Pambakian et al., 2000). This might provide good representational reconstruction of line length and limit the extent of contralesional deviation of the subjective midpoint. In patients with neglect and concomitant visual field defects, the reflexive contralesional pseudofoveal bias could instead exert its spatial influence without being counterbalanced by representational reconstruction of contralesional line length ahead of bisection. This might happen either because the line is incompletely inspected or because contralesional visual information gathered with the seeing field (and initially

Fig. 7 Second study: bisection of perceived 20 mm lines. Averaged percentage deviations from the midpoint of subjective line length (as measured from the marking of subjective line endpoints). The value of 0 on the abscissa indicates perfect performance. Negative values indicate contralesional deviation. Thin horizontal lines inside the graph represent the 95% confidence interval obtained from the N–H– sample considered in the first study.
projected to the intact left hemisphere) cannot be used by the damaged right hemisphere for building up a representational reconstruction of line extension (Gaffan and Hornak, 1997). We hypothesize that, in these patients, the scarce attentional attraction from the ipsilesional side of short lines and the lack of voluntary compensatory scanning of their contralateral side might leave bisection performance exclusively and erroneously influenced by the small contralateral ocular deviations enabling, in a purely reflexive way, eccentric fixations with the pseudofovea just across the border of the visual field cut. At the precise moment of bisecting very short lines, this could cause a spatially unregulated deviation in the direction of the field cut and the appearance of cross-over. With long lines, the small spatial effects of the pseudofoveal bias could be silenced by the spatially powerful ipsilesional deviation of attention caused by the long ipsilesional sector of the line.

In a third study, we specifically addressed this hypothesis by examining a patient with neglect and incongruous contralateral hemianopia, with an area of 5° of residual vision in the right eye and no sparing in the left one. We contrasted line bisections performed in monocular left-eye and right-eye viewing conditions and the corresponding spatial distributions of ocular fixations during the bisection of short (20 mm) and long (200 mm) lines.

**Third study: eye movements**

**Patient**

NH is a 65-year-old right-handed man. In October 2003, he sustained a parietal–temporal–frontal cortical and subcortical stroke in the right hemisphere (Fig. 8). The stroke resulted in left hemiplegia. At the moment of testing, 80 days later, his intellectual functions were within the normal range, with no memory or language impairment. Severe left-side extrapersonal neglect was found (letter cancellation: left 0/53, right 48/53; line cancellation: left 10/11, right 10/10; line bisection, 200 mm, ipsilesional deviation 56.5 mm; Wundt–Jastrow, left 48/53; line cancellation: left 10/11, right 10/10; line bisection, 20 mm, ipsilesional deviation 25.5 mm; Wundt–Jastrow, left 15/20, right 1/20). Static perimetry of the central 5–10° of residual vision in the left eye and incomplete hemianopia in the right eye and the screen was 47 cm. Long (200 mm) lines subtended 2.5° and short (20 mm) lines 2.5° of the visual angle. Lines were presented at the centre of the screen with their centre aligned to the patient’s head–body midsagittal plane. At the beginning of each trial, a calibration procedure was run. The patient was required to fixate a dot (diameter 2 mm) consecutively presented at positions corresponding to the left endpoint, left-half midpoint, midpoint, right-half midpoint and right endpoint of the line. Immediately after the calibration phase, the patient was required to fixate a dot positioned 5° below the centre of the line; the experimenter verified fixation and started presentation of the line by pressing the space bar on the computer keyboard. At the beginning of each trial, the hand of the patient holding the pencil was positioned on a switch aligned to the body midsagittal plane. The start of the bisection movement determined the release of

**Line bisection task**

Horizontal 200, 100 and 20 mm black lines were presented following a procedure similar to that of the first study. Ten lines of each length were bisected in three viewing conditions: (i) binocular viewing; (ii) monocular left-eye viewing (right eye patched); and (iii) monocular right-eye viewing (left eye patched). The patient was examined in three separate daily sessions, one for each viewing condition. In each session, different length lines were presented in separate blocks of trials. Blocks were administered in random order.

**Subjective endpoint task (i.e. perceived length of 20 mm lines)**

NH was asked to mark the endpoints of five horizontal lines in each viewing condition.

**Eye movement recording during the bisection of 20 mm lines**

In a separate session, horizontal and vertical eye movements accompanying the bisection of long (200 mm) and short (20 mm) black-on-white horizontal lines were recorded with a high spatial resolution infrared system (Permobil, Ober2 system; sampling rate 200 Hz) in two viewing conditions: left-eye viewing and right-eye viewing. Five trials were run in each condition. Left-eye and right-eye viewing trials were administered in random order in the same experimental session. The patient sat in front of the computer screen with his head blocked on a chin-rest. The distance between the eye and the screen was 47 cm. Long (200 mm) lines subtended 25° and short (20 mm) lines 2.5° of the visual angle. Lines were presented at the centre of the screen with their centre aligned to the patient’s head–body midsagittal plane. At the beginning of each trial, a calibration procedure was run. The patient was required to fixate a dot (diameter 2 mm) consecutively presented at positions corresponding to the left endpoint, left-half midpoint, midpoint, right-half midpoint and right endpoint of the line. Immediately after the calibration phase, the patient was required to fixate a dot positioned 5° below the centre of the line; the experimenter verified fixation and started presentation of the line by pressing the space bar on the computer keyboard. At the beginning of each trial, the hand of the patient holding the pencil was positioned on a switch aligned to the body midsagittal plane. The start of the bisection movement determined the release of
the switch and the marking of the event on the eye movement recording. The tip of the pen was modified so that the pressure of the pen on the screen triggered the closing of another switch and the marking of this second event on the eye movement recording. This procedure allowed the individuation of two phases in the recording: the first (phase 1) extended from the presentation of the line to the start of the bisection movement and the second (phase 2) from the start of the movement to the bisection of the line.

**Results**

**Line bisection task**

Angular transformation of percentage deviations of the subjective centre from the objective centre of the lines, measured in each trial, were submitted to a viewing condition (binocular, left eye, right eye) × line length (200 mm, 100 mm, 20 mm) ANOVA. Ipsilesional deviations were scored as positive values, contralesional deviations as negative ones (Fig. 9). A significant viewing condition × line length interaction was
found \( F(4,54) = 3.8, P = 0.008 \). Planned comparisons showed that in binocular viewing ipsilesional deviation in the bisection of 200 mm lines was less marked than in the left eye viewing condition (\( P = 0.03 \)). No significant difference was found between binocular and right-eye viewing conditions or between right-eye and left-eye viewing conditions. Viewing condition did not modulate the ipsilesional deviation found in the bisection of 100 mm lines. When 20 mm lines were bisected in monocular viewing, right-eye performance was virtually perfect and contralesional deviation corresponded to less than 1% of total line length. However, with the left eye contralesional deviation was 12 times higher (cross-over; left eye versus right eye, \( P = 0.001 \)). The contralesional deviation in left-eye viewing was also significantly higher than in the binocular viewing condition (\( P = 0.03 \)). No difference was found between right-eye and binocular viewing conditions.

**Subjective endpoint task (i.e. perceived length of 20 mm lines)**

Independently of viewing condition, NH marked the endpoints of 20 mm horizontal lines flawlessly. Errors ranged from 0 to 0.2 mm (binocular, left endpoint = 0.1 mm, right endpoint = 0 mm; left eye, left endpoint = 0 mm, right endpoint = 0.2 mm; right eye, left endpoint = 0.1 mm, right endpoint = 0 mm) and were so negligible that no analysis of corrected percentages of bisection deviation was performed.

**Eye movements during bisection of 200 and 20 mm lines**

For each trial, infrared reflection values measured at the five calibration positions were used to establish a linear correspondence between the eye-trace in the recording (independent variable) and the position of fixations over the line expressed in centimetres (dependent variable). For each trial, we calculated the averaged position of fixation and fixation times from the presentation of the line to the start of the bisection movement (phase 1), from the start of the movement to the bisection of the line (phase 2), and at the time of bisection (see Methods). Averaged fixation positions were submitted to a viewing condition (left eye, right eye) \( \times \) trial phase (phase 1, phase 2, bisection) ANOVA. Averaged fixation positions are reported in Fig. 10 and averaged fixation times in Fig. 11.

**200 mm lines**

Averaged fixation positions were submitted to a viewing condition (left eye, right eye) \( \times \) trial phase (phase 1, phase 2, bisection) ANOVA. Only a main phase effect was found \( F(1,4) = 11.03, P = 0.005 \), showing that in phase 1 fixation was significantly less shifted to the right of the line midpoint (3.0 cm) than in the other two phases (means: phase 2 5.53 cm; bisection 6.35 cm). Fixation times recorded in each trial were analysed with a viewing condition (left eye, right eye) \( \times \) trial phase (phase 1, phase 2) ANOVA. Only a main phase effect was found \( F(1,4) = 8.40, P = 0.04 \), showing that fixation time was significantly longer in phase 2 (2288 ms; left eye 2365 ms, right eye 2212 ms) than in phase 1 (1139 ms; left eye 1350 ms, right eye 928 ms).

**20 mm lines**

One right-eye viewing trial, in which no significant linear regression was present between the independent and the dependent variable, was discarded from the analysis. The ANOVA showed significant main effects (both \( P < 0.005 \)) and a significant viewing condition \( \times \) trial phase interaction \( F(7,14) = 11.5, P = 0.001 \). Planned comparisons showed that, in phase 1, in both viewing conditions fixation was slightly shifted to the right of the line midpoint (left eye versus right eye, not significant). In phase 2, left-eye fixation
shifted over the left endpoint of the line whereas right-eye fixation remained centred over the line midpoint (left eye versus right eye, $P < 0.0001$). At the moment of bisection these fixation positions remained virtually unchanged in both viewing conditions (left eye versus right eye, $P < 0.0001$).

Fixation times recorded in each trial were analysed through a viewing condition (left eye, right eye) x trial phase (phase 1, phase 2) ANOVA. Only a main phase effect was found [$F(1,7) = 15.63, P = 0.005$], showing that fixation time was significantly longer in phase 2 ($1688$ ms; left eye $1516$ ms, right eye $1860$ ms) than in phase 1 ($638$ ms; left eye $488$ ms, right eye $788$ ms).

For each viewing condition and each trial phase (1 and 2), we also measured the mean percentage of total fixation time spent in each of five discrete $0.5$ cm line sectors centred on the five fixation positions used in the calibration procedure (Fig. 10). When necessary, we considered two additional lateral sectors, one to the left and one to the right of the five central ones. During phase 1, the left eye remained preferentially positioned over the line sector immediately adjacent to the right of the central one and over the central one. In phase 2, fixation time peaked in the sector centred over the left endpoint of the line with the remaining time spent fixating the sectors respectively adjacent to its right and left side (i.e. beyond the contralesional line endpoint). With the right eye, in phase 1 fixation time peaked over the sector located to the right of the central one. In phase 2, half of the fixation time was spent on the sector immediately adjacent to the left of the central one, and the other half was equally distributed over the central sector and the one immediately adjacent to its right side. With the left eye, bisection was displaced $1.8$ mm (i.e. $9\%$ of total line length) to the left of the objective midline, whereas with the right eye bisection was displaced $0.4$ mm (i.e. $2\%$ of line length) to the right of the midline [$F(1,8) = 6.9, P = 0.03$].

**Discussion and conclusions**

In the third study, cross-over was found only when the neglect patient bisected short horizontal lines with the left eye, in which no sector of the contralesional visual field was spared. No cross-over was found when short lines were bisected with the right eye in which the central sector of the contralesional visual field showed sensitivity to high-contrast stimuli. Marking the endpoints of short $20$ mm lines was virtually perfect in both monocular viewing conditions. This demonstrated, as in the first and second studies, that cross-over was not due to confabulatory extension of the left side of the line. Long ($200$ and $100$ mm) lines were bisected ipsilesionally in both monocular conditions. The ipsilesional deviation was not significantly different between the two eyes. This indicates that cross-over in the monocular left-eye viewing condition was not linked to greater neglect severity than the right-eye viewing condition. The same result also implies that cross-over in the left-eye viewing condition was not accounted for by the amelioration of left unilateral neglect sometimes observed following patching of the right eye (Roth et al., 2002). Finally, the precise dependency of cross-over on the incongruity of the visual field defect between the two eyes limits the plausibility of the possible influence of eye-independent factors, such as pseudohemianopia (i.e. neglect for visual stimuli that evoke reliable electrophysiological responses; see Halligan and Marshall, 2002).

Studies by Ishiai and co-workers (Ishiai et al., 1992, 1995) clarified that neglect patients direct their gaze towards the subjective centre of the line immediately after line presentation and continue to fixate this point until they mark the centre there. Therefore, line length seems to be analysed by simultaneous perceptual judgement rather than serial searching. NH inspected short lines differently, depending on the eye he was using. Ocular scanning with the right eye (in which part of the contralesional visual field was spared) was quite similar to that documented by Ishiai and co-workers. Only
minor fixation shifts inside the central section of the line were observed when passing from phase 1 (from line presentation to the start of the arm movement) to phase 2 (from the start of the movement to the marking of the midpoint). With the left eye (showing no sparing of the contralesional visual field), fixations shifted from the central sector of the line in phase 1 to the contralesional left endpoint of the line in phase 2. These findings demonstrate that no compensatory scanning of the contralesional section of the line was made prior to the start of the bisection movement and that cross-over occurred as...
a by-product of a reflexive compensatory displacement of fixation towards the scotomatous area while directing the tip of the pen towards the subjective centre of the line. Eye movement recordings confirm the hypotheses we advanced based on the first study results. They also agree with Marshall and Halligan’s (1989) original proposal that cross-over is paralleled by ocular scanning of the contralesional side of the line.

We think that the relationship between neglect severity and cross-over calls for a cautious interpretation. At first sight, cross-over seems hardly to be explained by higher neglect severity along the directions crossing the retinotopically blind sector of the contralesional space. In fact, more severe neglect would have predicted maintenance of ipsilesional deviation at all line lengths rather than facilitated redirection of attention towards the contralesional space with short lines. However, following Chatterjee’s (1995) original suggestion, we considered the possibility that more severe neglect in the retinotopically blind space implicated stronger disruption of inhibitory mechanisms in the damaged hemisphere, a stronger tendency to confabulatory extension of the contralesional side of short lines and, consequently, a contralesional shift of the subjective midpoint. To investigate the influence of confabulatory completion on cross-over, in all of the three studies we asked neglect patients to mark the lateral endpoints of short (20 mm) lines. Errors in the individuation of the contralesional line endpoint were very negligible. When deviations in the bisection of 20 mm lines were corrected, taking the midpoint of subjective line length as reference, bisection performance remained unchanged. This generally suggests that the prevalence of cross-over along the directions of space in which both neglect and visual field defects are present can be dissociated from confabulatory contralesional extension of the line (though in some patients the two phenomena may be concomitant; Tegner and Levander, 1991; Chatterjee, 1995).

Regardless of whether or not they had concomitant hemianopia, both in the first and the second study neglect patients showed stronger ipsilesional deviation in the bisection of long lines and greater omission of contralesional items on cancellation tasks compared with all of the control patients without neglect. These findings reconfirm that the line bisection task is a sensitive measure of neglect. This was recently disputed by Ferber and Karnath (2001). These authors found that 40% of patients showing neglect on multiple-item cancellation tasks, out of a sample of 35 right-brain-damaged patients, showed no difference from controls on the line bisection one. In that study, however, lines to be bisected were always positioned with their right endpoint aligned to the right border of the sheet of paper; that is, shifted into the ipsilesional space. According to the authors, this was done to replicate the procedure adopted by Schenkenberg et al. (1980) and to use normative data from this latter study. However, it is well known that positioning the line to be bisected in the ipsilesional space usually improves neglect, eliminating any difference between the bisection performance of neglect and non-neglect patients, as demonstrated in the study of Schenkenberg et al. (1980). It is worth noting that in their study, Schenkenberg and co-workers also demonstrated that the pathological ipsilesional deviation of neglect patients is clear-cut when lines are positioned in the centre of the page (as conventionally done) or with their left endpoint aligned to the left edge of the page, that is, shifted into the contralesional space.

Our results may have relevant implications for competing accounts of the neglect syndrome and, more specifically, of line bisection performance. A number of hypotheses attribute the pathological ipsilesional deviation in the bisection of long lines to defective attention and/or representation of their contralesional side and simultaneous enhancement of the attentional and/or representational valence of their ipsilesional side (Anderson, 1996; Pouget and Driver, 2000). These interpretations predict that ipsilesional deviation should decrease or even disappear with diminishing line length because with very short lines the ipsilesional side does not effectively deviate attention and the influence of defective representation of the contralesional side diminishes. This prediction seems confirmed by the result of our group study as no difference in the bisection of 20 mm lines was found between the N+H– and N–H– groups (both groups bisected almost perfectly). The attentional–representational interpretation of ipsilesional bisection of long lines can be reconciled with contralesional bisection of short lines crossing the blind area of the neglected space if the mechanism redirecting attention in the contralesional direction is precisely individuated. Based on the findings of the present three studies, we propose that this mechanism probably consists of the spatially unregulated use of eccentric fixations with the pseudofovea which reflexively deviate ocular scanning towards the border of the contralesional scotoma.

At variance with attentional–representational interpretations of ipsilesional deviation in line bisection, it was recently proposed that, independently of the presence of visual field defects, in neglect patients the contralesional side of horizontal lines is not attentionally under-represented but, rather, subjectively perceived as compressed (Milner et al., 1993) or progressively more and more compressed when passing from the ipsilesional to the contralesional sectors of the line (Bisiach et al., 1994) (i.e. anisometric distortion). Cross-over per se seems generally more difficult to adjust with these interpretations because topological compression of the contralesional side of horizontal lines would predict ipsilesional bisection bias at all line lengths, though progressively decreasing with decreasing length in the case of anisometric compression. According to the same explanation, ipsilesional bisection should be found in all neglect patients and independently of both concomitant visual field defects and ocular scanning of the contralesional side of the line. Anisometric representation of horizontal space could still be accommodated with the absence of cross-over in neglect patients without visual field defects, by hypothesizing that very short lines are insensitive to the relatively low anisometric gradient of
size distortion suffered by these patients (as suggested, for example, by the moderate, though significant,ipsisectic deviation in the bisection of long 200 mm lines shown in the first study by N+H– patients). However, cross-over seems to contrast irremediably with the very severe gradient of spatial anisometric distortion suffered by neglect patients with hemianopia [suggested by the marked ipsilesional deviation in the bisection of long (200 mm) lines shown by N+H+ patients]. The possibility that in these patients the inspection of the contralesional side of short lines with the pseudofovea might still determine cross-over in spite of severe subjective line distortion is unlikely. In this sense, two alternatives can be envisaged. First, it can be hypothesized that in neglect patients with hemianopia the blind hemifield is just superimposed on a gradient of spatial distortion identical to that suffered by neglect patients without hemianopia. In this case, inspection with the pseudofovea should bring the line into the good hemifield and, as no significant change is introduced by the visual field defect on the gradient of size distortion to which short lines are insensitive, cross-over should be absent, just as in neglect patients without hemianopia. Secondly, it can be hypothesized that, since in patients with neglect and concomitant hemianopia ipsilesional bisection of long lines is exacerbated, the presence of hemianopia makes the gradient of distortion more severe in the seeing hemifield. In this case, bringing the line into the seeing hemifield should still produce ipsilesional rather than contralesional deviation compared with neglect patients without hemianopia, which was not the case in the findings from our study.

The findings from the three present studies point to the combination of visual field defect and neglect as a necessary condition for the appearance of cross-over. A smoother version of this conclusion could be formulated by considering the possibility that, with lines shorter than 2 cm, some degree of cross-over could be generally observed even in normal healthy subjects, because as the line gets shorter even normal subjects might be inclined to see the extent to the left of the centre as larger than it really is (Bradshaw et al., 1985, 1987). The combination of neglect and hemianopia might just exaggerate the normal tendency to shift the line midpoint slightly leftward. Nonetheless, the data from the present report first provide precise clues about the functional determinants of cross-over in unilateral neglect. Future investigations with techniques allowing the accurate mapping of the retinal sectors used for stimulus scanning (i.e. laser ophthalmoscopy) and the concomitant recording of arm–hand movements will further verify and define the visual and motor correlates of cross-over we have detailed.

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