Rightward and leftward bisection biases in spatial neglect: two sides of the same coin?

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Neglect patients, when asked to bisect a horizontal line, typically show large rightward errors with long lines and a decreased error with medium length lines. With very short lines the bisection bias reverses from the right to left side of the line physical centre (the so-called crossover effect). It is commonly pointed out that such a leftward bias is difficult to explain by traditional theories of neglect. Several accounts propose two distinct mechanisms, one that works for short lines and one that works for long. In the present study we demonstrated that the crossover effect can be explained by means of a unitary mechanism that derives from the space anisometry hypothesis. This hypothesis postulates that in neglect patients representational space is progressively ‘relaxed’ contralesionally and progressively ‘compressed’ ipsilesionally. In a series of five experiments, we investigated the crossover effect in 26 right-brain damaged patients: 17 with neglect without hemianopia, 4 with neglect and hemianopia and 6 without neglect or hemianopia. Patients were to bisect or extend lines of objectively and subjectively different lengths. The modulation of subjective length was created by an Oppel–Kundt illusion that is thought to resemble the distortion of representational space that occurs with neglect. All groups, except for the patients with neglect and hemianopia, were prone to the illusion. The rightward bias was reduced when the illusion induced a perceptual distortion opposite to that thought to underlie neglect. Importantly, the strength of the illusion decreased with reducing the physical line length and reversed with very short lines. These results argue for a simple and unitary explanation of the crossover effect in spatial neglect within the framework of the space anisometry hypothesis.

Keywords: crossover; space anisometry; space distortion; line extension; Oppel–Kundt illusion

Abbreviations: LE = Leftward extension; RE = rightward extension


Introduction

Patients with left neglect, when asked to mark the midpoint of a horizontal line, typically bisect the line to the right of the physical centre (Heilman and Valenstein, 1979; Schenkenberg et al., 1980) and this bisection bias increases as a function of line length (Bisiach et al., 1983). Hence, the bisection made by neglect patients shows large rightward errors with long lines and a decreased error with medium length lines. However, with very short lines the bisection bias reverses from right to left side of the physical centre of the line (the so-called crossover effect, Halligan and Marshall, 1988; Marshall and Halligan, 1989). The crossover effect is typically considered a challenge for traditional theories of neglect since they cannot explain a leftward bias (Doricchi et al., 2005). Therefore, numerous and somewhat complicated hypotheses were proposed to explain this effect (see for a review Monaghan and Shillcock, 1998). All of these explanations typically invoke the idea that there are two different attentional mechanisms at work, one for long and one for short lines (see Mennemeier et al., 2005, Table 1). As an example, in a recent paper Doricchi and co-workers (2005) proposed that the causes of crossover could be found in small reflexive compensatory displacements of eye fixations toward the contralesional space for short lines, whereas for long lines this effect was counter-balanced by a strong attentional shift to the right side of space. That is, the rightward attentional shift is strong for long lines but absent for the short lines because there is nothing on the right to attract attention. For short lines, compensatory left displacements of eye fixations, not
counterbalanced by attentional right displacements, are the cause of the leftward bisection bias.

In contrast to the attentional explanations of spatial neglect, it has been proposed (Gainotti and Tiacci, 1971; Milner, 1987) that rightward biases in neglect result from a general distortion of the representation of space in neglect patients. Following this hypothesis, the subjective space of neglect patients might be distorted in a non-Euclidean manner, producing a misrepresentation of the entire space, both for the contralesional and the ipsilesional field. Recently, Bisiach and co-workers (1998, 1999, 2002) proposed a representational framework, the space anisometry hypothesis, that seems to be able to account for behavioural phenomena in neglect. According to this idea, the representational medium, in which within- and between-objects spatial relationships are represented, is pathologically anisometric along the horizontal dimension. That is, the representational medium is progressively ‘relaxed’ toward the contralesional space and progressively ‘compressed’ toward the ipsilesional one in a logarithmic manner.

Several pieces of evidence support the space anisometry hypothesis. A rightward bias was found in the end-point task (Bisiach et al., 1994, 1996) in which patients were asked to reproduce left and right end-points of a previously seen horizontal line. In this task only a vertical line is presented at the centre of the page. Attentional theories of neglect, which argue that the left side of space is not well attended, would predict that patients would put right end-point disproportionally further from the central vertical line than the left end-point. In contrast to this prediction, neglect patients tend to place the contralesional left end-point disproportionally further in the neglected hemispace and the right end-point disproportionally nearer in the attended hemispace resulting in a rightward bias. This behaviour can only be explained as resulting from a misrepresentation of space: The same distance between two points is represented differently depending on its position in space. The same conclusion can be drawn from experiments using the line extension task (Bisiach et al., 1996; Chokron et al., 1997). In this task, neglect patients are asked to extend horizontal lines to double their length either rightwards or leftwards. The attentional account predicts that the half of the line to be extended should attract attention to the side of the space where the line was presented, thus producing a leftward under-extension. Opposite to this prediction, neglect patients tend to overextend lines contralesionally and underextend them ipsilesionally. Such a misrepresentation is not confined to the visual domain. When asked to compare the size of two objects, one to the left and one to the right of midline, by touch (the tactile size matching task, Milner et al., 1998), neglect patients tend to underestimate the size of the contralesional object. The left object in a pair of objects of the same size is judged smaller than the right object. This effect would result according to the space anisometry hypothesis because the representation of space on the left is larger, and hence the size of the object relative to the representation of space is smaller (Milner et al., 1993; Milner and Harvey, 1995; Milner et al., 1998; Irving-Bell et al., 1999). All these results are in line with the representational metric proposed by the space anisometry hypothesis and are difficult or impossible to explain within an attentional bias theory of neglect.

The space anisometry hypothesis can also account for line length effects that are hard for the attentional bias hypothesis to explain. For example, in a study by Ricci et al. (2000) patients with neglect were asked to bisect lines. The stimuli were lines that were all the same length, but differed in the size of the segments that composed the line. Lines composed of short segments were judged by healthy subjects as appearing longer than lines composed of long segments. In neglect patients, however, the rightward errors were larger when bisecting lines that appeared longer than when bisecting subjectively shorter lines. With all of these stimuli there is no reason to postulate different rightward shifts of attention because both types of lines were symmetrical and of the same physical length. Thus, as pointed out by the authors, their findings are better explained by a change in the magnitude of internal representations, not by a change in the magnitude of displacement of attention. Again, in a very recent paper by Rode and co-workers (2006), two neglect patients were asked to perform different tasks: (1) to draw objects from memory, (2) to copy drawings (3), to extend lines both rightward and leftward, (4) to perceptually judge the extent of two rectangles, one to the left and one to the right. The authors found (1) left-sided enlargement of drawings both from memory and by copying, (2) leftward overextension of lines and (3) underestimation of the left rectangle. These results are in line with the idea that in neglect patients the horizontal representational medium is anisometric. The extent of objects and distances is represented differently depending on their position in space. Thus, line bisection and extension tasks show effects that are best accounted for by the space anisometry hypothesis.

Interestingly, the nature of the spatial distortion in neglect according to the anisometry hypothesis is similar to the Oppel–Kundt illusion (Fig. 1). Quoting Bisiach (1997, p. 491): ‘the distortion underlying neglect and related phenomena has been likened to a pathological remapping of an Euclidean onto a logarithmic scale, with spatial expansion on the contralesional and compression on the ipsilesional side, giving rise to something similar to the Oppel–Kundt illusion’. This illusion consists of the phenomenon that a filled space usually looks longer/larger than an empty space of the same size (Kundt, 1863; Watt, 1994). Consistently with Bisiach’s hypothesis, Ricci et al. (2004) found that an anisometric background which creates an illusory distortion of space can modulate neglect. The authors used line bisection, line extension and cancellation
tasks and they reported that when the illusion induced a representation of distances and lengths opposite to the hypothesized representational deficit, the errors of neglect were reliably reduced. These results showed that the rightward bias typically present in patients with neglect can be explained by an anisometric representation of space that is similar to the Oppel–Kundt illusion.

One phenomenon of neglect that has been very difficult to explain by any of the existing theories is the crossover effect, which is the tendency of neglect patients to bisect very short lines to the left to the physical centre. Here we investigate whether this effect can be explained by the space anisometry hypothesis. If this theory can explain this phenomenon, it would be strong evidence in support of this theory over an attentional bias theory. Thus, the main thrust of the present paper is to ascertain whether such a distortion has different effects depending on the horizontal extent of lines.

**Methods**

**Subjects**

Five healthy controls without history of neurological disease and signs of general cognitive impairment (mean MMSE: 28.2 30; SD: 2.5) were included in the first experiment. Their age (mean = 74.8 years, SD = 9.52) and education (mean = 6.2 years, SD = 1.64) did not differ from those of brain-damaged patients included in experiments two \( t(14) = 1.018, P = 0.326 \) and \( t(14) = -1.018, P = 0.326 \), respectively; three \( t(9) = 0.878, \ P = 0.403 \) and \( t(9) = -0.276, \ P = 0.789 \), respectively; four \( t(7) = 0.342, \ P = 0.742 \) and \( t(7) = 0.628, \ P = 0.550 \), respectively and five \( t(9) = 0.386, \ P = 0.709 \) and \( t(9) = 1.076, \ P = 0.310 \), respectively.

**Stimuli and procedure**

The task consisted of bisecting bars of different lengths. The bars were presented at a reading distance on a landscape A4 sheet of white paper aligned with the sagittal midline of the subjects. The subjects bisected five 10 mm thick horizontal bars of 20, 40, 80 or 160 mm in length. A modified version of the Oppel–Kundt illusion was produced by using 1 mm thick vertical lines inside the horizontal bar (Fig. 1). Subjects were asked to bisect bars in the following four conditions: (I) empty bar (control); (II) evenly filled, thought to be perceived as longer than the control (Ricci et al., 2000); (III) filled with lines progressively compressed from left to right (thought to be perceived as longer to the right); (IV) filled with lines progressively compressed from right to left (thought to be perceived longer to the left). For clarity we named experimental conditions II, III and IV as their presumed resulting

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**Fig. 1** Stimuli to be bisected reproducing the Oppel–Kundt illusion.
percepts (i.e. ‘Longer’, ‘Right-longer’, ‘Left-longer’), whereas condition I is named as ‘Control condition’.

The scale used in positioning vertical lines within the horizontal bar was decimal (with a constant distance between lines of 8 mm) in the ‘Longer’ condition, whereas an exponential function \( y = e^{0.2626x} \) was used in the ‘Right-longer’ and ‘Left-longer’ conditions with opposite directions of increment (i.e. with the origin of the scale to the right in the ‘Right-longer’ and to the left in the ‘Left-longer’ condition).

In order to prevent the build-up of a consistent strategy, stimuli were totally randomized within the series and all participants received a different stimulus sequence. In addition, to prevent a ‘vertical line counting’ strategy to find the middle of the horizontal line, subjects received the following instructions: ‘Now I’ll show you a sheet of paper with a horizontal line. This line can have or not have vertical lines inside. Your task is to bisect the horizontal bar as quickly and as accurately as possible. Keep in mind that trying to count vertical lines could be misleading: Vertical lines are irrelevant for finding the physical centre because they are never placed at the physical centre of the bar and sometimes you’ll see a different number of vertical lines to the left and right sides’. During the task, the experimenter made sure that subjects were following these instructions and, if not, the particular trial was rerun and instructions explained again.

Line bisection errors were measured with approximation to the nearest millimetre. Positive values indicate a rightward error and negative values a leftward error. The mean bisection error was recorded separately by subject, condition, length and illusory effect.

### Results

Mean bisection errors by illusory condition and length in healthy subjects are shown in Table 1 and Fig. 2.

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<th>160</th>
<th>80</th>
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<th>20</th>
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<tbody>
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<td>Right-longer</td>
<td>7.80</td>
<td>3.00</td>
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</table>

A two-way ANOVA with the four illusory conditions and the four line lengths as within-subjects factors was performed. The main effect of illusory conditions was significant \( F(3,12) = 29.663, P < 0.001 \). Also the main effect of line lengths was significant \( F(3,12) = 4.829, P < 0.05 \). More importantly the interaction between illusory conditions and line length was significant \( F(9,36) = 19.619, P < 0.001 \). To further investigate the effect of interaction, three two-way ANOVAs were carried out separately for the three illusory conditions with respect to the empty (control) line.

### Discussion

The results of the present experiment showed that when presented with the Oppel–Kundt illusion, healthy individuals show a pattern of line bisection similar to that objects in patients with neglect. This effect, however, was only observed when the segmentation of space is asymmetrically distorted in a manner suggested by the space anisometry hypothesis to occur in neglect. Moreover, in both
‘Right’- and ‘Left-longer’ conditions the effect of illusion decreased with decreasing line length and reliably reversed for very short lines.

These results are in keeping with psychophysical evidence (Bulatov and Bertulis, 1999; Bulatov et al., 1997) gathered using the traditional Oppel–Kundt illusion in a size comparison task. The authors asked healthy subjects to estimate in free vision the perceived length of a test figure (the empty part of the Oppel–Kundt figure) by adjusting it to be equal to a reference figure (the filled part of the Oppel–Kundt figure). They used reference stimuli of different lengths and found that size comparison errors (that is, the measure of the distortion of length perception induced by the illusion) decreased with decreasing length of the reference stimulus. These data and the ones found in the present experiment, thus, indicate that in healthy subjects the strength of the Oppel–Kundt illusion gradually decreases when using stimuli occupying little space. More importantly, they demonstrate that the effect of such an illusion reverses for very short lines: empty space appears larger (instead of smaller) than filled space. The present study provides the additional information that this distortion of space affects where the midline is perceived to be.

Our results also indicate that, at least for the present subjects, the distortion of space observed in the ‘Right-longer’ and ‘Left-longer’ conditions does not merely result because the space has been segmented by vertical lines. In the ‘Longer’ condition, in which the vertical lines are equally spaced, we observed neither a deviation from midline during bisection nor an effect of line length.

**Experiment 2**

In the Experiment 1 we provided evidence that in healthy subjects the Oppel–Kundt illusion produced an alteration of the mental representation of space that resembles the bisection behaviour observed in neglect patients. Moreover, such a spatial distortion is found to have different effects depending on the horizontal extent of lines. That is, with long lines it produced a displacement of the perceived midline towards the right whereas with very short lines a displacement of the perceived midline towards the left.

In the present experiment we follow up on this finding by examining bisection behaviour on a similar task with neglect patients. Prior work has indicated that the bisection performance of neglect patients is modulated by the Oppel–Kundt illusion (Ricci et al., 2004). Neglect patients showed a worsening of the rightward bias for lines that appeared longer to the right and a leftward bias for lines that appeared longer to the left. This modulation of the bisection bias provides evidence that the representation of space in neglect patients is distorted according to the space anisometry hypothesis. This effect, however, was demonstrated only with long lines.

In the present experiment brain-damaged patients with and without neglect performed the same task of Experiment 1 to explore the effect of the Oppel–Kundt illusion on the rightward bisection bias at different line lengths. If the space anisometry hypothesis is correct and space is represented in a manner consistent with an Oppel–Kundt illusion, the prediction here is to find a reduction of the strength of such an illusion by reducing the physical length of the line. We expect a modification of the results found by Ricci et al. (2004) in which the Oppel–Kundt illusion induced a rightward with lines that were longer to the right and a leftward bias with lines that were longer to the left. More precisely, by reducing line length, the space anisometry hypothesis predicts a reduction of both these rightward and leftward biases. With very short lines, the space anisometry hypothesis predicts an inversion of the directional bias induced by the Oppel–Kundt illusion. That is, a leftward bisection error in the ‘Right-longer’ condition and a rightward bisection error in the ‘Left-longer’ condition.

**Methods**

**Subjects**

Data were collected from 11 right brain-damaged patients without signs of general cognitive impairment (mean MMSE: 26.5/30; SD: 2.7), who gave informed consent to be included in the experiment. All of them were right-handed. Demographic and clinical data are reported in Table 2. Patients did not suffer from visual field defects as assessed by means of a kinetic Goldmann perimetry. Unilateral neglect was assessed by means of the following three tests: (a) Albert cancellation task: Patients were presented with a modified version (Driver and Halligan, 1991) of Albert’s cancellation task (Albert, 1973) composed of 50 short black segments (2 cm long and 0.5 mm thick) printed on an A4 sheet of paper placed in front of the subject at reading distance. The patients’ task was to cross out all lines with no limitation of time. The number of uncrossed lines homogeneously distributed in an area confined to the left sub-array or comprising the right sub-array was recorded (see Neppi-Modona et al., 2002 on page 1922 for details). (b) Letter H cancellation task (Diller and Weinberg, 1977): Patients were presented with 6 rows of letters (104 Hs and 208 distracting letters) distributed in 52 columns, printed on an A3 sheet of white paper, and asked to cross out all the Hs. The number of omitted Hs to the left was recorded. (c) Line bisection task: Patients were required to bisect a series of five 20 cm long and 2 mm thick black horizontal lines. Errors were measured with approximation to the nearest millimetre. Positive values indicate a rightward error and negative values a leftward error.

Participants were included in two groups, according to the presence/absence of neglect signs, as following: (1) six brain-damaged patients with neglect (N+1/N+6); (2) five brain-damaged patients without neglect (N−). The criterion used to select neglect patients was the following: five or more omissions in the Albert cancellation task and/or five or more omissions in the left in the letter H cancellation task and/or five or more omissions in the left in the letter H cancellation task and/or a mean rightward error of 10 mm or more in bisecting lines (i.e. exceeding three SDs (SD = 1.7 mm) from the N− and 5C controls’ mean, that was 0.2 mm to the left of true centre). This criterion was chosen according to the procedure used by Bisiach and colleagues (1998).
Crossover and space anisometry

Table 2  Demographic and clinical data

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<th>Age</th>
<th>Education</th>
<th>Lesion site (CT)</th>
<th>Length of illness (months)</th>
<th>MMSE</th>
<th>Albert</th>
<th>Diller</th>
<th>Line bisection (mm)</th>
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<tr>
<td>N+H+1</td>
<td>M</td>
<td>72</td>
<td>9</td>
<td>TPO</td>
<td></td>
<td>24</td>
<td>39</td>
<td>/</td>
<td>68</td>
</tr>
<tr>
<td>N+H+2</td>
<td>F</td>
<td>85</td>
<td>2</td>
<td>ci-O</td>
<td></td>
<td>29</td>
<td>29</td>
<td>/</td>
<td>45</td>
</tr>
<tr>
<td>N+H+3</td>
<td>M</td>
<td>59</td>
<td>5</td>
<td>TPO</td>
<td></td>
<td>27</td>
<td>39</td>
<td>86</td>
<td>66</td>
</tr>
<tr>
<td>N+H+4</td>
<td>M</td>
<td>74</td>
<td>8</td>
<td>TO</td>
<td></td>
<td>30</td>
<td>27</td>
<td>29</td>
<td>60.8</td>
</tr>
</tbody>
</table>

Note: F = frontal; T = temporal; P = parietal; O = occipital; bg = basal ganglia; ci = capsula interna; th = thalamus.

Stimuli and procedure

Same as in Experiment 1.

Results

Length effect with N+ patients: empty line condition

To determine whether we replicated prior findings and obtained a significant crossover effect in our neglect patients, we examined the effect for the empty line condition alone. To determine the relationship between line length and rightward bisection errors we performed for N+ patients, a one-way ANOVA with line length as a within-subjects factor. The main effect of line length was significant \([F(3,15) = 28.052, P < 0.001]\) with bisection errors decreasing in a linear fashion (polynomial analysis, \(F = 56.372, P < 0.001\)) with decreasing line length. A series of Bonferroni-corrected post hoc one sample t-tests showed that bisection errors were reliably different from zero for line length of 160 mm \([t(5) = 6.630, P < 0.005]\), of 80 mm \([t(5) = 4.871, P < 0.01]\), of 40 mm \([t(5) = 4.136, P < 0.01]\) and, more importantly, 20 mm \([t(5) = -3.246, P < 0.01]\) indicating a reliable crossover effect (-1.28 mm). Thus, the crossover effect was observed in our sample of neglect patients.

Illusory effect

A mixed three-way ANOVA with group (N+ and N−) as a between-subjects factor and illusory conditions (empty, longer, right-longer, left-longer) and line length (160, 80, 40, 20) as within-subjects factors was performed on the deviation from true centre. Mean bisection errors by each group of subjects and illusory and length conditions are shown in Table 3 and for the sole N+ group in Fig. 3.

Neglect patients made bisection errors reliably greater \([F(1,9) = 26.531; P < 0.005]\) than controls (N−). The main effect of illusory condition was significant \([F(3,27) = 112.168, P < 0.001]\). Also the main effect of line length was significant \([F(3,27) = 33.657, P < 0.001]\). N+ and N− patients performed reliably in a different manner with respect to both illusory conditions \([F(3,27) = 37.399, P < 0.001]\) and line length \([F(3,27) = 13.977, P < 0.001]\). The interaction between illusory conditions and line length was also significant \([F(9,81) = 61.134, P < 0.001]\) and the triple interaction with group was significant \([F(9,81) = 21.187, P < 0.001]\). Three subsequent two-way ANOVAs were carried out separately for the three illusory conditions with respect to the empty (control) line in the two groups of patients.
in long lines decreased with decreasing line length, and actually switched to the left of true centre for short lines. This finding indicated that N+ patients performed similarly to controls (N− patients) when the illusion enhanced the side of space for which they do not show neglect.

Empty versus ‘Left-longer’. N+ and N− patients bisected ‘Left-longer’ lines significantly further to the right than empty (control) lines \( [F(1,9) = 96.990; P < 0.001] \). The N+ patients were more sensitive to the illusion than N− patients as evident by a significant interaction between group and illusion condition \( [F(1,9) = 6.012; P < 0.05] \). The main effect of line length \( [F(3,27) = 32.862; P < 0.001] \) was significant and this effect was larger \( [F(3,27) = 17.227; P < 0.001] \) for N+ than with N− patients. Importantly, however there was no differential effect of line length between empty and filled lines \( [F(3,27) = 2.060, P = 0.129] \) and N+ and N− patients performed in the same manner \( [F(3,27) = 0.337; P < 0.799] \). This finding indicates that the strength of the illusion does not change depending on line length.

Empty versus ‘Right-longer’. N+ and N− patients bisected ‘Right-longer’ lines significantly further to the right than empty (control) lines \( [F(1,9) = 45.317; P < 0.001] \) and N+ and N− patients performed in the same manner \( [F(3,27) = 4.426; P = 0.062] \). The main effect of line length \( [F(3,27) = 90.185, P < 0.001] \) was significant and this effect was larger \( [F(3,27) = 33.881; P < 0.001] \) with N+ than with N− patients. Importantly, the interaction between Empty and ‘Right-longer’ lines was significant \( [F(3,27) = 17.844, P < 0.001] \), indicating that the illusionary effect decreased in decreasing line length, and the effect was similar in N+ and N− patients \( [F(3,27) = 1.691; P = 0.192] \). That is, the bisection to the rightwards error

<table>
<thead>
<tr>
<th></th>
<th>N+</th>
<th>N−</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>160  80  40  20</td>
<td>160  80  40  20</td>
</tr>
<tr>
<td>Empty</td>
<td>22.97 6.50 2.57 0.128</td>
<td>3 1.48 0.16 0.4</td>
</tr>
<tr>
<td>Filled</td>
<td>26.40 7.77 2.87 0.03</td>
<td>1.2 0.24 0.4</td>
</tr>
<tr>
<td>Left-longer</td>
<td>−0.97 −3.73 −1.03 0.53</td>
<td>−2.28 −2.4 −0.76 0.64</td>
</tr>
<tr>
<td>Right-longer</td>
<td>36.80 13.67 3.63 −1.97</td>
<td>10.64 4.56 1.28 −1.36</td>
</tr>
</tbody>
</table>

Table 3 Experiment 2. Line bisection errors as a function of illusory conditions and line length in N+ and N− patients.

Fig. 3 Experiment 2. Mean bisection errors as a function of illusory condition and line length in N+ patients.
Discussion
The results of the present experiment are consistent with the idea that the representation of space is specifically distorted in patients with neglect. Just as for healthy subjects in Experiment 1, the results of the present experiment showed that in brain-damaged controls without neglect (N=−) the Oppel–Kundt illusion had an effect on line bisection only when using asymmetrical arrangements of vertical lines. With stimuli inducing an over-estimation of the right part of the line, brain-damaged controls misplaced the midline to the right of the physical centre, a behaviour that mimics the typical bisection error in neglect. Moreover, this effect decreased with line length and inverted using very short lines.

In neglect patients the modulation of the bisection errors was evident in all illusory conditions. Lines that appeared evenly longer than empty (control) lines produced an increment of the rightward bisection error. Lines that appeared longer to the right produced a worsening of the rightward bias, whereas lines that appeared longer to the left produced leftward bisection errors. These results are in line with those found by Ricci et al. (2004) and, more importantly, are consistent with the idea that the representation of space in neglect is distorted along the horizontal meridian in the way proposed by the space anisometry hypothesis.

The novel finding, here, regards the effect of line length to the perceived midline. With ‘Right-longer’ and ‘Left-longer’ conditions the strength of the Oppel–Kundt illusion decreased with decreasing line length. More importantly, the effect of the illusion reverses with very short lines indicating that the strength of the spatial distortion underlying neglect depends on the horizontal extent of lines. Thus, this bisection behaviour and, particularly, the inversion of the spatial direction of illusion bias with very short lines provides an explanation of the crossover effect that is consistent with the distorted representation of space as proposed by the space anisometry hypothesis.

Experiment 3
The present experiment was designed to control for an alternative explanation of the crossover effect, that is the idea that the crossover is related to a context effect (Marshall et al., 1998; Ricci and Chatterjee, 2001). According to this idea, the crossover emerges because the perceived midpoint of a line is related to the line’s length relative to other lines with which it is presented. Support for this idea comes from a study performed by Marshall and co-workers (1998), who found a disappearance of the crossover effect when lines of different lengths were bisected by patients in separate sessions. However, it remains unclear why such a context effect is able to produce an altered perception of the midpoint only for short but not for long lines. Regardless, we carried out a third experiment to determine, as we predict, that context does not play a significant role in the crossover effect. More specifically, we used the same types of stimuli as in the first and second experiment but presented in groups blocked for length. The prediction of the present experiment is that a crossover effect will be observed similar to that in the prior two experiments, ruling out the possibility that our prior results were driven by context.

Methods
Subjects
Six patients with neglect and without hemianopia (N+7/N+12) and without signs of general cognitive impairment (mean MMSE: 26.2/30; SD: 2.1) took part in the present experiment. None of these individuals participated in Experiment 2. The criterion of selection was the same as in Experiment 2. Demographic and clinical data are reported in Table 2.

Stimuli and procedure
All stimuli and procedures were the same as in Experiments 1 and 2 with the exception of the order of presentation. Subjects bisected lines of only one specific length within a given session. Each of the four sessions was conducted on separate days. The order of line-length sessions was counterbalanced among patients. Within each session, the four different illusory conditions were presented randomly and each patient received a different order.

Results
Length effect
To determine whether we replicated prior findings and obtained a significant crossover effect in our neglect patients even with stimuli blocked for length, we examined the effect for the empty line condition alone. To determine the relationship between line length and bisection errors we performed a one-way ANOVA on bisection errors. The main effect of line length was significant \( F(3,15) = 19.398, P<0.001 \) and such bisection errors decreased in a linear fashion (polynomial analysis, \( P=53.367, P<0.001 \)) with decreasing the line length. A series of Bonferroni-corrected post hoc one sample \( t \)-tests showed that the bisection errors were reliably different from zero and in opposite directions for line lengths of 160 mm \( \tau(5) = 6.731, P<0.001 \) and 20 mm \( \tau(5) = -6.900, P<0.001 \), indicating a reliable crossover effect \( (-1.73 \text{ mm}) \). Thus, the crossover effect was observed in our sample of neglect patients even when lines were presented blocked for length.

Illusory effect
Mean bisection errors as a function of illusory and length conditions are shown in Table 4 and Fig. 4. A two-way ANOVA with the four illusory conditions and the four line lengths as within-subjects factors was performed. The main effect of illusory conditions was significant \( F(3,15) = 17.603, P<0.001 \). Also the main
Table 4  Experiment 3. Line bisection errors as a function of illusory conditions and line length in N+ patients

<table>
<thead>
<tr>
<th>Illusory Condition</th>
<th>N+</th>
<th>160</th>
<th>80</th>
<th>40</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
<td></td>
<td>12.00</td>
<td>3.60</td>
<td>−1.07</td>
<td>−1.73</td>
</tr>
<tr>
<td>Filled</td>
<td></td>
<td>16.27</td>
<td>5.37</td>
<td>1.03</td>
<td>−0.77</td>
</tr>
<tr>
<td>Left-longer</td>
<td></td>
<td>0.13</td>
<td>−3.03</td>
<td>−3.77</td>
<td>0.60</td>
</tr>
<tr>
<td>Right-longer</td>
<td></td>
<td>20.43</td>
<td>7.13</td>
<td>0.67</td>
<td>−2.50</td>
</tr>
</tbody>
</table>

Discussion
In the present experiment neglect patients showed a crossover effect even presenting stimuli in a blocked manner with respect to the line length. Importantly, the illusory effect induced by our manipulation remained unchanged. The longer line condition produced rightward bisection errors greater than in the empty (control) line condition. Lines that appeared longer to the right produced a worsening of the rightward bias, whereas lines that appeared longer to the left reversed this effect and yielded leftward bisection errors. With ‘Right-longer’ and ‘Left-longer’ conditions the strength of the Oppel–Kundt illusion decreased with decreasing line length and the illusory effect reverses with very short lines, indicating that the strength of the spatial distortion underlying neglect depends on the horizontal extent of lines. The results thus indicate that the crossover effect cannot be solely due to the context in which stimuli are presented. As pointed out by Ricci and Chatterjee (2001), context effects could contribute to the crossover effect but it does not completely account for it. They found that bisection errors were modulated by the line length of a previous stimulus both for long and short lines, but the crossover only occurred for short lines. The results of the present experiment and those of Experiment 2 considered together provide strong evidence in support of the space anisometry hypothesis, which suggests that space is distorted in a manner much like that of an Oppel–Kundt illusion. Importantly, the distortion of the representation of space in neglect has a reduced effect for short than for long lines. For very short lines, as observed in the Oppel–Kundt illusion, the distortion reverses, which explains the shift of the bisection error from right to left.

Experiment 4
The present experiment is designed to rule out another possible explanation of our results which shows the
development of the illusory effect with decreasing line length, and actually switched to the right of true centre for short lines. Thus, the neglect in these patients was ameliorated by an Oppel–Kundt illusion that acted in reverse to the way in which the space anisometry hypothesis argues that neglect patients represent space.

A series of Bonferroni-corrected post hoc paired-sample t-tests showed that the inversion of the illusory effect for lines at very short length (20 mm) with respect to the empty line was significant for both ‘Right-longer’ [t(5) = 58.452, P < 0.005] and ‘Left-longer’ [t(5) = −5.576, P < 0.005] lines. This finding is consistent with the idea that with very short lines the illusion reverses its effects, producing a leftward bisection error in the ‘Right-longer’ condition and a rightward bisection error in the ‘Left-longer’ condition.

The results of the present experiment and those of Experiment 2 considered together provide strong evidence in support of the space anisometry hypothesis, which suggests that space is distorted in a manner much like that of an Oppel–Kundt illusion. Importantly, the distortion of the representation of space in neglect has a reduced effect for short than for long lines. For very short lines, as observed in the Oppel–Kundt illusion, the distortion reverses, which explains the shift of the bisection error from right to left.

The present experiment is designed to rule out another possible explanation of our results which shows the
rightwards. If the latter prediction is upheld, illusion of distorted space is lost, the results should not we should still find a modulation of bisection errors in the which would also occur in patients with occipital lesions, an attraction of attention to the filled part of the figures, As to the space anisometry hypothesis, the attentional bias hypothesis would predict a worsening of rightward bisection errors in ‘Right-longer’ condition because more vertical lines are positioned to the right (and thus attracting more attention to the right). Similarly, it would predict leftward bisection errors or a reduction of rightward bisection errors in ‘Left-longer’ condition because attention is shifted or attracted to the left, that is where vertical lines are closer.

Some help in differentiating between these two possibilities arises from the fact that the occipital cortex seems to be the neural basis for visual illusions (Hirsch et al., 1995; Ffytche and Zeki, 1996; Weidner and Fink, 2007). Hemianopic patients and neglect patients with visual field defects (hemianopia) resulting from occipital lesions are insensitive to visual illusions (Vallar et al., 2000; Daini et al., 2001, 2002; Ricci et al., 2004). Hence, the logic is simple. If the results of the previous experiments are due to an attraction of attention to the filled part of the figures, which would also occur in patients with occipital lesions, we should still find a modulation of bisection errors in the same direction as in previous experiments. On the other hand, if the space anisometry hypothesis is correct, once the illusion of distorted space is lost, the results should not differ across conditions. If the latter prediction is upheld, it would provide strong evidence for space anisometry hypothesis.

**Methods**

**Subjects**

Four patients with neglect and hemianopia assessed by a kinetic Goldmann perimetry (N+H+1/N+H+4) and without signs of general cognitive impairment (mean MMSE: 27.5/30; SD: 2.6) took part in the present experiment. All of them were right-handed and none participated in Experiments 2 or 3. The criterion of selection was the same as in Experiment 2. Demographic and clinical data are reported in Table 2.

**Stimuli and procedure**

The stimuli were the same as in previous experiments. Two patients (N+H+1 and N+H+3) received a randomized order of presentation (as in Experiment 2) and the other two (N+H+2 and N+H+4) a blocked order of presentation (as in Experiment 3).

**Results**

Mean bisection errors as a function of illusory condition and length are shown in Table 5.

A two-way ANOVA with the four illusory conditions and the four line lengths as within-subjects factors was performed. Only the main effect of line length was significant \( F(3,9) = 128.463, P < 0.001 \). Importantly, the main effect of illusory conditions \( F(3,9) = 1.073, P = 0.408 \) and the first-order interaction with line length \( F(9,27) = 1.054, P = 0.246 \) were not significant. This result indicates that line bisection error was consistent across conditions.

**Discussion**

The results of the current experiment indicate that our results in Experiments 2 and 3 cannot be explained by an attraction of attention to the filled part of the figures. As such, they provide strong additional evidence in support of the space anisometry hypothesis. The results of the present experiment with N+H+ patients showed that only line length influenced performance. Importantly, for these four patients with hemianopia, condition had no effect in modulating the rightwards and leftwards bisection errors. Patients with occipital lesions are not prone to illusion but are still sensitive to possible attentional modulation. Thus, we can rule out the possibility that effects found in control subjects and neglect patients without hemianopia are due to a shift of attention to the more salient part of space, that is the region where more vertical lines are present. Instead, the results strongly corroborate the predictions of the space anisometry hypothesis, which suggests the representation of space in neglect is anisometric. As such, the distortion depends on the extent of a line to be bisected, resulting in a leftward bisection bias with very short lines.

**Experiment 5**

This experiment was designed to further rule out the possibility that an attentional bias can explain our results. To do so, we used a line extension task rather than a line bisection task because the attentional bias and the space anisometry hypothesis make different predictions about performance of patients with neglect. In the line extension

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**Table 5** Experiment 4. Line bisection errors as a function of illusory conditions and line length in N+H+ patients

<table>
<thead>
<tr>
<th>N+H+</th>
<th>160</th>
<th>80</th>
<th>40</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
<td>34.35</td>
<td>7.40</td>
<td>−3.15</td>
<td>−2.20</td>
</tr>
<tr>
<td>Filled</td>
<td>37.35</td>
<td>10.40</td>
<td>−0.85</td>
<td>−5.20</td>
</tr>
<tr>
<td>Left-longer</td>
<td>33.75</td>
<td>6.30</td>
<td>−1.00</td>
<td>−4.65</td>
</tr>
<tr>
<td>Right-longer</td>
<td>35.75</td>
<td>13.00</td>
<td>0.00</td>
<td>−4.00</td>
</tr>
</tbody>
</table>

Downloaded from https://academic.oup.com/brain/article-abstract/130/8/2070/311353 by guest on 23 April 2019
task, individuals are asked to extend a series of horizontal lines in order to double their length (Chokron et al., 1997; Bisiach et al., 1998). The end that they are asked to extend is always positioned at midline.

The attentional bias hypothesis predicts that attention should be attracted to the side of space from which the line should be extended. For example, the degree of line extension should be shorter when a line has to be extended leftward than extended rightward. Contrary to this prediction, when required to extend horizontal lines either rightwards or leftwards, neglect patients tend to overextend them contralesionally and underextend them ipsilesionally (Chokron et al., 1997; Bisiach et al., 1998). This results in a similar bias to that of the canonical line bisection task: the centre of the reproduced line is placed at the right of the objective midpoint.

In the present experiment, thus, we utilized the same procedure of line extension task by Ricci et al. (2004) in which lines to be extended were presented against different backgrounds, some of which gave the illusion of anisometry of space. In order to examine the crossover effect in this representational task, we used not only long lines as in the Ricci et al.’s experiment but also very short lines. The prediction of the space anisometry hypothesis is that with long lines, there will be an improvement of the rightward bias when patients are to extend lines placed in a background inducing an illusion that counteracts the space distortion hypothesized to underline neglect (‘Left-longer’ condition). In addition, it predicts a worsening of rightward bias when the illusory background produced a similar hypothesized distortion of the representation of space (‘Right-longer’ condition). With very short lines we expect to find an inversion of this pattern of modulation, as for the previous experiments in which neglect patients bisected lines.

**Methods**

**Subjects**

Six neglect patients without hemianopia (N+12/N+17) and without signs of general cognitive impairment (mean MMSE: 25/30; SD: 1.7) took part in this experiment, one of whom also participated in Experiment 3. The criterion used to select neglect patients was the same as in the previous experiments. Demographic and clinical data are reported in Table 2. Control subjects were not included in the present experiment by the fact that it is well known in literature (i.e. Bisiach et al., 1998; Ricci et al., 2004) that when healthy subjects extend lines to the left and right, they typically do so very close to the actual size of lines.

**Stimuli and procedure**

Patients were required to extend, by means of a pencil, 1 mm thick black horizontal lines in order to double their length. There were two series of lines consisting of 10 items each: lines of 20 mm in length and lines of 80 mm in length. The latter condition replicates that of Ricci et al. (2004) while the former is novel. Half of the lines had to be extended rightward and half leftward starting from their right or left endpoints, respectively. Lines were presented with the right or left endpoints (that is the point from which to start to extend lines) at the centre of an horizontal A4 sheet of white paper placed at reading distance and aligned to the vertical body midline of the patient. The lines to be doubled were presented in three different illusory isometric and anisometric backgrounds (Fig. 5) as in the experiment by Ricci and colleagues (2004). That is (I) evenly spaced vertical lines that served as the baseline (Control); (II) unevenly spaced vertical lines progressively compressed from right to left (‘Left-longer’); (III) unevenly spaced vertical lines progressively compressed from left to right (‘Right-longer’). The same mathematical functions were used in positioning vertical lines as in previous experiments.

The order of conditions by line length, direction of extension and illusory backgrounds was totally counterbalanced among patients, as in Ricci and colleagues’ paper (2004). Errors were measured with approximation to the nearest millimetre. The deviation between the physical line length and the reproduced line length was measured. Positive values indicate an over-extension (i.e. an extension longer than 2 or 8 cm, respectively) and negative values an under-extension (i.e. an extension shorter than 2 or 8 cm, respectively). For each patient, we noted: (1) The mean
leftward extension (LE); (2) The mean rightward extension (RE); (3) The LE/RE ratio between LE and RE. The LE/RE ratio is a laterality index typically used in studies on the line extension task and it provides a useful and normalized measure of the patients’ performance: a value greater than 1 indicates an over-extension of left segment (LE is greater than RE) with respect to the right segment, whereas a value lower than 1 indicates an over-extension of right segment (LE is lower than RE) with respect to the left segment. This measure is independent from the actual size of lines reproduced. Also in this task, patients were instructed not to count vertical lines. The experimenter made sure that the instructions were followed and, if not, the particular trial was rerun and instructions explained again.

**Results**

The mean LE/RE ratio by each patient was entered in two one-way ANOVAs with illusory background conditions as a within factor, separated for the two line lengths. The data are shown in Table 6 and Fig. 6.

**Lines of 80 mm in length**

The main effect of illusory backgrounds \[F(2,10)=35.644, \quad P<0.001\] was significant. A series of post hoc t-tests with Bonferroni correction showed a reliably reversal \(P<0.05\) of the rightward bias in the ‘Left-longer’ (LE/RE ratio = 0.90) condition and a reliably increment \(P<0.05\) of the rightward bias in the ‘Right-longer’ (LE/RE ratio = 1.36) with respect to the control (evenly filled background) condition (LE/RE ratio = 1.10). This result represents a replication of the results obtained by Ricci et al. (2004) and, more importantly, are in direct contrast with the prediction of an attentional explanation of neglect. The attentional hypothesis would have predicted the opposite results. Instead, our findings strongly support the idea that the representation of space in neglect is horizontally distorted as predicted by the space anisometry hypothesis.

**Lines of 20 mm in length**

The main effect of illusory backgrounds \[F(2,10)=24.392, \quad P<0.001\] was significant. A series of post hoc t-tests with Bonferroni correction showed a reliably increment \(P<0.01\) of the rightward bias in the ‘Left-longer’ (LE/RE ratio = 1.19) condition and a reliably reversal \(P<0.05\) of the rightward bias in the ‘Right-longer’ (LE/RE ratio = 0.94) with respect to the control (evenly filled background) condition (LE/RE ratio = 1.08). This result indicates that we obtained a reversal of the effect of the illusion with very short lines, thus corroborating the interpretation of the crossover effect within the space anisometry hypothesis.

**Discussion**

The results of the fifth experiment provided additional evidence that our results are not compatible with the attentional bias hypothesis. They do so in numerous ways. First, we replicated the findings of Ricci and colleagues. A background inducing an illusory spatial anisometry (or distortion) that counteracts the one thought to underlie neglect (‘Left-longer’ condition) is able to reduce the rightward bias. Rather, the background induces patients to underextend lines toward the filled space on the left (or overextend lines toward the empty space on the right). By the same token, a background inducing an illusory spatial anisometry (or distortion) similar to the one thought to underlie neglect (‘Right-longer’ condition) worsens the rightward bias by, again, inducing patients to underextend lines toward the filled space on the right (or overextend lines toward the empty space on the left).

Second, the present experiment provides additional evidence for the space anisometry hypothesis because a crossover effect is observed for short lines that are 20 mm in length. The effect of the Oppel–Kundt illusion reverses with very short lines and the effect on line bisection in neglect patients also reverses. Contrary to the prediction of

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Experiment 5. N+ patients’ performance in line extension task as a function of illusory conditions and line length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 mm Line</td>
</tr>
<tr>
<td></td>
<td>LE</td>
</tr>
<tr>
<td>Filled (control)</td>
<td>87.67</td>
</tr>
<tr>
<td>Left-longer</td>
<td>81.23</td>
</tr>
<tr>
<td>Right-longer</td>
<td>109.63</td>
</tr>
</tbody>
</table>

Fig. 6  
Experiment 5. Mean LE/RE ratio as a function of illusory condition with line of 80 mm (A) and 20 mm (B) of length in N+ patients.
any attentional account of neglect, our results strongly support the space anisometry hypothesis in explaining both rightward bisection biases with long lines and leftward bisection biases with very short lines, thus providing a reason of the crossover effect.

**General discussion**

In the present series of five experiments using line bisection and line extension tasks, we investigated the effect of the Oppel–Kundt illusion in modifying the representation of space in healthy subjects and in brain-damaged patients with and without neglect. The results of these experiments strongly support the space anisometry hypothesis of neglect. In the first experiment, we were able to simulate in healthy controls the bisection behaviour shown by neglect patients when bisecting lines of different lengths. Importantly, when the illusion had the effect of inducing an anisometric representation of space, the bisection bias decreased with decreasing line length and reliably reversed for very short lines.

The same was true in the second and third experiments with brain-damaged patients that compared those with and without neglect. The rightward bisection biases in neglect patients were increased by inducing an illusory spatial anisometry similar to the one thought to underlie neglect. Moreover, inducing an illusory spatial anisometry that counteracts the one thought to underlie neglect reduced the rightward bias. Importantly, such a distortion of the representation of space in neglect has a reduced effect for short than for long lines. For very short lines, the distortion has the effect of reversing the rightward bias, which explains the shift of the bisection error from right to left. Importantly, all these effects do not depend on the context in which stimuli are presented.

In the fourth experiment we examined bisection in hemianopic patients, who are known to be insensitive to visual illusions. Studying such patients thus is an optimal tool for differentiating between an explanation of the bisection results in terms of an attentional shift as compared to an explanation in terms of an anisometric representation of space. In this experiment we found that the illusory effect disappears, indicating that the representation of space in neglect is anisometric and it depends on the extent of a line.

Finally, in the fifth experiment, using a line extension task, we again found that inducing an illusory spatial space anisometry counteracting the one thought to underlie neglect reduces the rightward bias. Inducing an illusory spatial anisometry similar to the one thought to underlie neglect worsens the rightward bias. Importantly, the effect of the Oppel–Kundt illusion reverses with very short lines, as found for the line bisection task. Thus, these results further support the space anisometry hypothesis in explaining the crossover, against the prediction of an attentional account of neglect.

These outcomes argue for a simple, but not simplistic, explanation of the crossover effect in spatial neglect within the framework of the space anisometry hypothesis (Bisiach et al., 1998, 1999). The representation of space in neglect is anisometric along the horizontal meridian and the strength of such a distortion depends on the extent of the lines. Importantly, the effect of the anisometric distortion of space representation in neglect, typically inducing a rightward bias with long lines, is also responsible to the leftward bias with very short lines.

Contrary to the previously proposed explanation of crossover (i.e., Monahagan and Shillcock, 1998; Doricchi et al., 2005; Mennemeier et al., 2005), our results indicate the need for only one mechanism to explain the patients’ performance both for long and short lines. In the recent paper by Doricchi and colleagues (2005), the authors claimed that representational interpretations of neglect (Milner et al., 1993; Bisiach et al., 1994; Milner and Harvey, 1995; Milner et al., 1998) would predict rightward bias for all line lengths. However, here we predicted and found that decreasing the line length, decreased the spatial distortion progressively and inverted its effect on very short lines. These prior predictions by Doricchi and colleagues probably arise from the lack of consideration of how an Oppel–Kundt-like distorted representation would vary with varying line length. Here, we have demonstrated that the space anisometry hypothesis, by which space is represented progressively ‘relaxed’ contralesionally and progressively ‘compressed’ ipsilesionally, produces such a spatial distortion able to predict the behaviour of neglect patients in bisecting very short lines.

With regards to the explanation proposed by Doricchi and colleagues (2005) of an involvement of small compensatory eye fixations toward the left side to account for the crossover effect, two other points should be stressed: (1) They require the supposition of two mechanisms (Monahagan and Shillcock, 1998; Mennemeier et al., 2005) instead of one, which is more consistent with the principle of economy, parsimony and simplicity in scientific theories and; (2) Advocate a casual role of eye fixations and movements in the genesis of a phenomenon, which does not seem highly plausible. As convincingly pointed out by Sumio Ishiai (2006), following his work covering almost two decades, eye-fixation patterns in neglect patients can be an useful tool to understand mechanisms underlying neglect but they are not an explanation of the neglect disorder. Indeed, he claimed that neglect does not disappear even when patients are forced to orient the gaze contralesionally. In our opinion, neglect patients do not move the eyes towards the left, because there is no left side of the world on which to shift the gaze. Therefore, eye-pattern disorders seem more plausibly to be an effect and not the cause of neglect.

A final point that deserves some considerations is the asymmetry of the effect of the Oppel–Kundt illusion in modulating rightward and leftward errors. With respect to
inducing leftward errors (crossover). In the same vein, representational anisometry reverses for very short lines rightward errors. Again, in patients with neglect the on the ipsilesional side of representation, inducing patients, with long lines such a misrepresentation produces similar to the effect of the Oppel–Kundt illusion. In neglect this non-linear metric could reflect a logarithmic scale healthy subjects. Following the space anisometry hypothesis, this idea, we calculated the difference in absolute value between biases in the ‘Right-longer’ or the ‘Left-longer’ conditions and the Empty condition for any line length (Table 7). We subsequently carried out two two-way ANOVAs with the two illusory conditions and the four line lengths as within-subjects factors. For both the 5 healthy controls and the 12 neglect patients we found the same reliable effects but in opposite directions (as previously described): a main effect of illusory conditions \( F(1,4) = 14.400, P < 0.05 \); \( F(1,11) = 9.631, P < 0.05 \), respectively, a main effect of line length \( F(3,12) = 23.125, P < 0.001 \); \( F(3,33) = 37.151, P < 0.001 \), respectively and, more importantly, an interaction between illusory conditions and line lengths \( F(3,12) = 7.101, P < 0.005 \); \( F(3,33) = 3.009, P < 0.005 \), respectively.

These findings suggest that even the visual system of healthy humans does not build an ideal representation of the metrics of the visual world. This is evident from the slight leftward bias present in healthy subjects when bisecting a line: The so-called pseudo-neglect effect (Bowers and Heilman, 1980; Jewell and McCourt, 2000). As an outcome of a slightly distorted mapping of external space onto an internal representation, the leftward bisect error could indicate that the left part of a line appears slightly longer than the right side. This is the same logic used to explain both rightward bias for long lines and leftward bias for short lines shown by patients with neglect. Thus, the same non-linear metric producing misrepresentation of the external world could be responsible for rightward errors for long lines and crossover for short lines in neglect patients and for pseudo-neglect in healthy subjects. Following the space anisometry hypothesis, this non-linear metric could reflect a logarithmic scale similar to the effect of the Oppel–Kundt illusion. In neglect patients, with long lines such a misrepresentation produces a spatial expansion of the contralesional and compression on the ipsilesional side of representation, inducing rightward errors. Again, in patients with neglect the representational anisometry reverses for very short lines inducing leftward errors (crossover). In the same vein, in healthy subjects the same effect of a short line for neglect patients is induced by a slight distortion of space, resulting again in similar leftward errors (pseudo-neglect). Thus, the results from the series of experiments we report here strongly support the space anisometry hypothesis of spatial neglect.

| Table 7 Absolute illusory effect with respect to the empty line |
|---------------------|---------------------|---------------------|---------------------|---------------------|
|                     | C                  | N+                 |                     |                     |
|                     | 160                | 80                 | 40                  | 20                  |
| Left-longer         | 3.12               | 0.76               | 0.40                | 0.76                |
| Right-longer        | 7.20               | 2.60               | 0.92                | 0.32                |

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