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The vertical–horizontal illusion in hemi-spatial neglect

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ABSTRACT

The vertical–horizontal illusion is a robust phenomenon of length mis-estimation between two orthogonal lines. This illusion involves an anisotropy component that makes the vertical line appear longer than the horizontal one and a bisection component that makes the bisected line shorter than the bisecting one. Six patients presenting a moderate left hemi-neglect (N-patients) were compared to four right brain damaged patients without neglect (RH-patients) and with control participants in the perception of various spatial configurations of the vertical–horizontal illusion. Relative to controls, we found that both components of the illusion increased in patients: the anisotropy component rose from 5 to 11% and 10% (for N- and RH-patients, respectively) and the bisection component from 17 to 22% and 20% (for N- and RH-patients, respectively). In addition, we found that an horizontal-'T' figure oriented to the left produced much less bias than the same figure oriented to the right. These results are discussed in light of explanations based on attentional disengagement from an image junction and strength of the representation of objects extending over the neglected side.

1. Introduction

In the contemporary literature on spatial neglect, a debate prevails between representational and attentional accounts of left neglect after right brain damage (for a review, see Kerkhoff, 2001). A central aspect of the representation account is a perceptual distortion of objects in the left part of visual space (e.g., Ferber & Karnath, 2001; Milner & Harvey, 1995). Perceptual distortions also occur in observers with no neurological damages for specific stimuli such as the vertical–horizontal illusion. The purpose of the present study is to compare the strength of this illusion between right brain damage and control participants, in order to better understand which aspects of the perceptual distortion are responsible for the neglect effects.

Visual illusions often provide important clues for perceptual mechanisms (Gregory, 1991) and the vertical–horizontal illusion is a strong and popular example of perceptual distortion (Künnapas, 1955, 1957; Valentine, 1912/1913). When observers have to judge the length of a vertical and a horizontal line of the same physical length (see Fig. 1A and B), they typically over-estimate the length of the vertical line. Two main hypotheses have been made in the literature to explain the processes leading to the vertical bias, one related to the depth interpretation of two-dimensional drawings (Gregory, 1991, 1997; Williams & Enns, 1996; Woodworth, 1938), and the other to some intrinsic properties of the visual system (e.g., Künnapas, 1955).

According to the first hypothesis, the illusion figure is seen in perspective in such a way that the vertical segment is interpreted as a vertical line in a slanted plane receding into the distance. For instance, Woodworth (1938) argued that observers should perceive the stimuli extending in depth, out of the picture plane. This depth hypothesis relies on the misapplication of size-constancy scaling by assuming that the vertical dimension is subject to a foreshortening of objects lying on the (invisible) ground plane. The size-constancy scaling would lead to a vertical line length overestimation. In agreement with this hypothesis, vertical overestimation increases in natural scenes, presumably because more pictorial cues are available (e.g., Von Collani, 1985; Williams & Enns, 1996).

The alternative hypothesis to explain the vertical bias relies on some intrinsic properties of the visual system, more specifically the visual field anisotropy. In general, the closer a line extends toward a surrounding frame, the longer it appears (Künnapas, 1955). Because the overall visual field (i.e., left and right eyes combined) is a horizontally oriented ellipse, vertical lines will generally be closer to the boundary of the visual field than will the horizontal lines, and hence vertical lines should appear longer. Experiments to test this hypothesis were carried out by Prinzmetal and Gettleman (1993).

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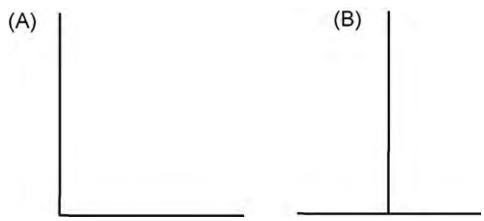

Fig. 1. Two visual illusions of length. Wolfe et al. (2005) called stimulus. (A) The vertical–horizontal illusion and stimulus. (B) The bisection illusion. In each, the vertical line appears to be longer than the horizontal line.

They showed that the illusion was reduced with monocular presentation, presumably because the monocular visual field is more circular than the binocular one.

While both hypotheses are still investigated, it is clear that they cannot fully account for the length illusions by themselves. In particular, the vertical–horizontal illusion is strongly affected by the spatial configuration of the figure and by its orientation in the image plane (Künnapas, 1955). In a recent study, Wolfe, Maloney, and Tam (2005) studied a wider range of stimuli than just the traditional illusion configurations. Each of their stimuli consisted of two-line segments joined at a point (Fig. 1). They named Fig. 1A, the "vertical–horizontal illusion" and Fig. 1B, the "bisection illusion". The magnitude of the two illusions varied with the viewing conditions, but the former illusion is usually stronger than the latter. They developed a model that combined a preference for a 3D interpretation of intersecting lines as orthogonal with a bias toward interpreting the stimulus configuration as slanted away from the line of sight (both of them are well-known prior constraints for the visual interpretation of scenes; Mamassian & Landy, 1998). Contrary to the prediction based on the orthogonal preference hypothesis, they found that deviations from a right angle in the vertical–horizontal configuration (Fig. 1A) led to an increase in illusion only if the angle was made obtuse. If the angle was made acute, a decrease in the illusion, and sometimes a reversal, resulted. This result is inconsistent with a model containing only assumptions about a preference for orthogonality.

In spite of its long history, a complete explanation of this phenomenon is still elusive (for a recent review, see Wolfe et al., 2005). One of the reasons for the elusiveness is that there are at least two separate factors at play (Künnapas, 1955). The first factor is an anisotropy between vertical and horizontal segments, i.e., a bias to overestimate the vertical length. The necessary second factor is a length bisection bias. According to this latter bias, a line that is bisected in two parts will appear shorter than if it were not interrupted (Finger & Spelt, 1947). We proposed a simple model of the vertical–horizontal illusion for various configurations of figures containing a vertical and a horizontal segments (see Mamassian & de Montalembert, 2010). This model is based on two bias parameters combined with the uncertainty to discriminate two lengths. The first bias parameter (parameter '*a*') stands for the anisotropy component of the illusion and represents the overestimation of a vertical segment relative to the horizontal one. The magnitude of this anisotropy bias was on average 6% in adult human observers. The second bias parameter (parameter '*b*') stands for the bisection component of the illusion and represents the underestimation of a segment when it is bisected. The magnitude of this bisection bias was on average 16%. This model involves a third parameter ('*c*') that is proportional to the uncertainty to estimate the length of a segment. This parameter is equal to 0.10.

In the present study, we were interested in how a population of right brain damaged-patients presenting left hemi-spatial neglect interpreted this illusion. The characteristic disturbance of unilateral spatial neglect is a deficient response to stimuli presented to the side contra-lateral to the affected brain hemisphere (Heilman, Watson, & Valenstein, 2003). Spatial neglect is observed following damage to various cortical regions including the parietal, temporal and frontal lobes (Karnath, Berger, Küver, & Rorden, 2004) or subsequent to subcortical lesions such as damage to the thalamus, putamen or globus pallidus (Karnath et al., 2004). Spatial neglect selectively affects different reference frames and regions of space such as personal, peripersonal and extrapersonal space (Buxbaum, 2006). Furthermore, patients sometimes neglect the left side of visual objects (object-based neglect) irrespective of their location is space (Driver & Mattingley, 1998).

Indeed, recent studies indicate that patients with visuo-spatial neglect tend to underestimate horizontal magnitudes in contralesional space. It has been recently hypothesised that this behaviour might be due to anisometry of space perception. Neglect patients tend to bisect horizontal lines ispsilesionally and underestimate the contralesional half of a line (e.g., Bisiach, Ricci, Lualdi, & Colombo, 1998) as well as horizontal objects located in the contralesional space (e.g., Milner & Harvey, 1995).

The following experiment aims at testing spatial perception deficit in left hemi-neglect patients with the use of the vertical–horizontal illusion. In particular, we were interested in comparing performances of right brain damage patients for stimuli oriented to the left *versus* to the right, and we hypothesized that left neglect patients should be impaired to analyze stimuli oriented to the left. We also propose to use this illusion to explore 3D perception of right brain damage patients, who might be specifically impaired in processing 3D scenes.

2. Methods

2.1. Participants

A total of six patients with left neglect (*N*) (mean age = 70.6 years, SD = 13.6, range = 43–78 years) and four patients with right brain damaged without neglect (RH) (mean age = 69.3 years, SD = 5.6, range = 62–75 years) participated in the experiment. Seven patients had a first single unilateral stroke (ischemic *N* = 7) in the right cerebral hemisphere and three other patients had a right hematoma (located in the internal capsule, and/or the thalamus, or the basal ganglia). All patients were right-handed and had no history of psychiatric disorders or dementia. The neuropsychological evaluation of each patient revealed no language disorders and no signs of apraxia or agnosia; none of the patients showed major verbal memory difficulties. All of them had a preserved comprehension of complex sentences. We created a program using Matlab to test hemianopia in patients. They were asked to detect whether a vertical or a horizontal line was present on a computer screen. Targets were presented in the left, right or both hemi-fields. None of them presented hemianopia or any other visual field deficit. This was confirmed with the BEN test (Azouvi et al., 2002; Rousseaux et al., 2001). We evaluated the severity of the spatial neglect for each patient using a set of clinical tests that is frequently used to assess neglect (Azouvi et al., 2002) including two visuo-motor exploratory tasks (line bisection and letter cancellation), a reading task, and a drawing copy task. In all tasks, the center of the display was located on the mid-sagittal plane of the patients' trunk; they were free to move their head and eyes. The patients' demographic and neurological features are summarized in Table 1.

Twelve participants (mean age = 62.42 years, SD = 10.5, range = 47–78 years) with no history or evidence of neurological damage served as controls. Ten of them were right-handed and two were left-handed. There were no difference in terms of age between the group of control participants and the group of patients ($F(1,20) < 1$, NS).

All patients and control participants had normal or corrected-to-normal visual acuity.

All participants gave informed consent prior to the study, but were naive concerning the specific aims of the experiment.

2.2. General neuropsychological evaluation

The neuropsychological neglect examination found no signs of spontaneous head and gaze deviation toward the right or the left side of space. All patients presented visuo-spatial and visuo-graphic impairments and their performance on executive function tests were generally mildly impaired (i.e., problems organizing and initiating actions).

For the Line Bisection Test, positive deviations were rightward for all right-brain-damage patients. The percentage of deviation corresponds to ((left distance − half of stimulus line length)/(half of stimulus line length)) × 100. A deviation greater

Table 1
Demographic and neurological data on the six neglect patients and four right brain damaged patients. For line bisection, positive deviations are rightward, percentages correspond to: ((left distance − half of stimulus line length)/(half of stimulus line length)) × 100. (*) A deviation greater than 11.1% is considered pathological (Schenkenberg et al., 1980). For cancellation tests, left/right correct responses are reported. The landscape drawing, consisting of a central house with two trees on each side, was scored by assigning two points to the house and one point to each tree that was completely copied (Gainotti et al., 1972). For the reading task a "+" means a correct reading of the text (i.e., no dyslexia of neglect).

Patient	Gender/age	Days from lesion onset	Etiology	Locus of lesion (R: right, L: left)	Line bisection (% deviation)	Letter cancellation (max 30 left/30 right)	Landscape drawing (max 6)	Reading task
N1	F/75	41	Ischemic	R. temporal, parietal lobes	−0.3	25/29	5	+
N2	F/77	90	Ischemic	R. temporal, parietallobes	+7.2	21/30	3	+
N3	M/78	95	Hematoma	R. thalamic	+2.6	26/30	3	+
N4	F/74	26	Ischemic	R. temporal, parietal lobes	+4.8	22/30	6	+
N5	F/43	32	Hematoma	R. capsulo-lenticular	+2.1	23/28	5	+
N6	M/77	41	Ischemic	R. parietal lobe	+13.1*	20/30	2	+
RH1	M/62	112	Ischemic	R. parietal lobe	−2.5	30/30	5	+
RH2	M/75	62	Ischemic	R. parietal lobe	+8.3	30/30	4	+
RH3	M/72	49	Ischemic	R. temporal, parietal lobes	+6.5	29/30	6	+
RH4	F/68	89	Hematoma	R. thalamic	+3.8	28/29	5	+
Controls (N = 12)	62.4 ± 10.5				1.2 ± 6.3	30/30	6	+
RH-patients (N = 4)	69.3 ± 5.6	78.0 ± 28.1			4.0 ± 4.7	29.3 ± 1.0/29.8 ± 0.5	5.0 ± 0.8	+
Neglect (N = 6)	70.6 ± 13.6	54.2 ± 30.3			3.9 ± 5.2	22.4 ± 2.3/29.6 ± 0.9	3.8 ± 1.6	+

than 11.1% is considered pathological (Schenkenberg, Bradford, & Ajax, 1980). In our study, bisection deviations ranged from 0.3 to 13%. In the letter cancellation task, the six right brain damage patients, diagnosed with neglect, showed little left neglect, characterized by more omissions on the left side of the sheet of paper; five patients (P1, P2, P4, P5 and P6) started to cancel the page on its right side. During the neuropsychological evaluation, patients had to copy a landscape consisting of a central house with two trees on each side. This task was scored by assigning two points to the house and one point to each tree that was completely copied (Gainotti, Messerli, & Tissot, 1972). Three patients (2, 3 and 6) performed poorly on this task (i.e., they omitted important details on the left side of their copy). It is important to note that, neglect patients' performance on this clinical neuropsychological evaluation supported a little or a mild form of neglect in visuo-spatial tasks. Control participants also completed the entire neuropsychological evaluation. In the Line Bisection Test, five of them showed a leftward bias (mean 3.2%), which is a well-known phenomenon named "pseudo-neglect" (Rueckert, Deravanesian, Baboorian, Lacalamita, & Repplinger, 2002).

2.3. Apparatus

All experiments were conducted on a 13-in. MacBook computer. The monitor was calibrated for luminance (brightness setting at 50% and contrast setting at 100%). It was set at a resolution of 1024 × 768 pixels and ran at a refresh rate of 60 Hz. The experimental stimuli were created with Matlab V.730 (Mathworks, Sherborn, MA, USA) and displayed with the PsychToolbox (V1.05; Brainard, 1997; Pelli, 1997).

2.4. Stimuli

All stimuli consisted of two-line segments joined at a point. The two lines formed one of three figures: an 'L', a 'T', or a '+'-sign, at different orientations: 0°, 90°, 180°, or 270° (Fig. 2). One line was colored in blue and the other one in red. They were displayed on a uniform white background (luminance set to 40 cd/m^2). The length of the horizontal line was fixed, whereas the length of the vertical line varied from trial to trial. The size of the standard line (i.e., the horizontal line) could be 156 pixels (6° of visual angle) or 117 pixels (4.5° of visual angle). When the stimulus length was 156 pixels, the line width equaled 6 pixels (and when it was 117 pixels long, it equaled 8 pixels). The method of constant stimuli was used to manipulate the aspect ratio of the figure. In this method, instead of being presented in "ascending" or "descending" order, the levels of a certain property of the stimulus were not related from one trial to the next, but presented randomly. This prevented the participant from being able to predict the level of the next stimulus, and therefore reduced errors of habituation and expectation. Eleven aspect ratios (i.e., vertical length/horizontal length) were chosen equally spaced on a log-scale between 0.81 and 1.23 (an aspect ratio of one means that the vertical is equal in length to the horizontal).

2.5. Procedure

The experiment took place in the experimenter's office, which was illuminated by dim light coming from a window in front of the participants. It lasted for about 1 h; all patients were able to complete the experimental tasks (i.e., they were able to maintain their attention the whole time, Robertson, Tegnér, Tham, Lo, & Nimmo-Smith, 1995). The display was viewed from approximately 57 cm, although subjects were free to move their head. A trial began with the presentation of a small fixation cross in the center of the display area for 500 ms, followed by a blank screen for 500 ms. The stimulus was then presented for 1000 ms, binocularly (Prinzmetal & Gettleman, 1993), followed by a blank screen until the observer responded by pressing a key. The next trial would then follow immediately.

Participants were asked one of two questions in separate blocks in random order: (1) is the blue line longer than the red one? (2) is the red line longer than the blue one? The advantage of this task was that participants were not focusing directly on the vertical–horizontal dimensions. In all cases, participants had to press the space bar to answer YES and not press it to answer NO (go/no-go task). A training set was presented before the session and no feedback was provided.

For each observer we measured first their red–blue judgment, and then we converted it into the percentage of times they responded that the vertical line was longer than the horizontal one.

In total, a session was composed of 704 stimuli presented in random order. We divided all configurations into four groups (see Fig. 2): the 'L' configuration (L1, L2, L3 and L4, top row; L2, L3 and L4 are obtained from L1 by turning it in steps of 90°), the vertical-'T' (T1 and T3, middle row), the horizontal-'T' (T2 and T4), and the '+'-sign configuration (P). To equate the number of judgments on each figure, for one presentation of the 'L' configuration, the 'T' configuration was presented two times and the '+'-sign four times. Participants ran two sessions, so they had to judge 1408 stimuli during the experiment. The 1408 trials were broken into 16 blocks of 88 trials each (20 judgments of each stimulus configuration), with resting breaks between blocks). Throughout the data collection, the experimenter sat on the opposite side of the computer monitor, at a location where she could monitor gaze direction. Before initiating each block, the experimenter ensured that the participant's gaze was directed to the center of the screen.

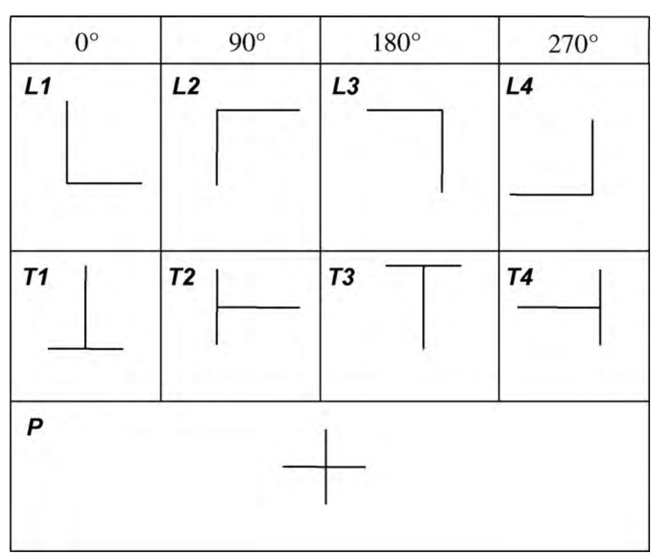

Fig. 2. Stimuli were grouped in four classes: the L-configuration at different orientations (L1, L2, L3 and L4; L2, L3 and L4 are obtained from L1 by turning it in steps of 90°), the horizontal-T configuration (T1 and T3), the vertical-T configuration (T2 and T4), and the "+"-configuration (P).

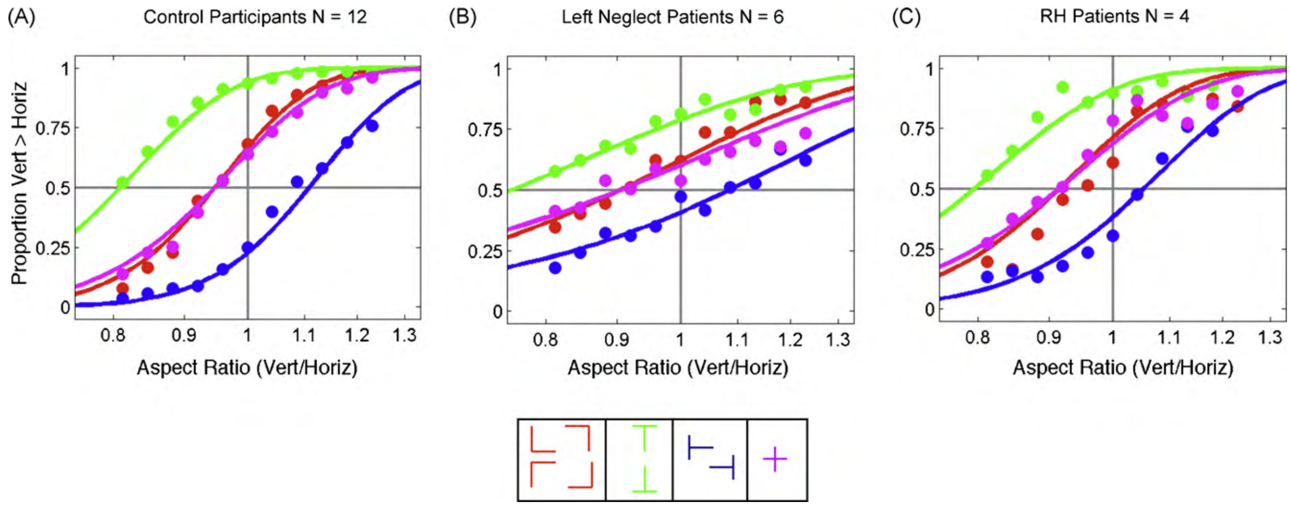

Fig. 3. Results for the four stimuli classes. The proportion of times the vertical segment was perceived longer than the horizontal is shown against the aspect ratio of the figure for the four classes of stimuli. Colours in the psychometric function represent the classes of stimuli shown in Fig. 2. Data were pooled across all control participants (A: $N = 12$) left neglect patients (B: $N = 6$) and right brain damaged patients without neglect (C: $N = 4$).

For each observer and each configuration, we computed the point of subjective equality (PSE). The PSE corresponds to the length at which a comparison stimulus (for instance here the vertical line) is perceptually equal to the standard stimulus length (here the horizontal line). This value represents the required length of a vertical line for participants to respond that "the vertical line is longer" than the horizontal one on 50% of the presentations.

3. Results

Fig. 3 shows the proportion of times participants decided that the vertical segment was longer than the horizontal one, as a function of the aspect ratio, for each of the four configurations. The solid lines show the best fit of the late-noise model adjusted to the empirical data (Mamassian & de Montalembert, 2010). Data for our three groups of participants are well accounted for by our model. The model includes an anisotropy parameter '*a*' that accounts for the length biases in the 'L'-shaped and '+'-sign figures and predicts that both figures should have the same point of subjective equality (PSE). This prediction is satisfied for the control participants and patients (N- and RH-patients). The model also includes a bisection parameter '*b*' that accounts for the difference between the horizontal-'T' and vertical-'T' figures and predicts that the vertical-'T' should lead to the strongest vertical–horizontal illusion. This prediction is also satisfied for our three groups of participants.

The magnitude of the illusion for the different classes of figures is determined by the position of the point of subjective equality to judge the length of the horizontal and vertical segments. For instance, if the horizontal segment of length 6° of visual angle is matched to a vertical segment whose length is 5.71° of visual angle, the magnitude of the illusion equals 5% (or equivalently a value of parameter 'a' equals to 1.05).

There is no difference between stimuli of different lengths so for the latter analyses we pooled all stimuli together ($\chi^2(1) < 1$, NS). For all participants (controls, N-patients and RH-patients), the magnitude of the illusion is maximal for the vertical-'T' configuration, namely around 20% of illusion. In other words, the vertical segment should be presented 20% shorter than its physical length in order to be perceived equal to the horizontal segment. For the horizontal-'T' configuration we find around −9% of illusion (i.e., the vertical line needs to be presented 9% longer than its physical length to be perceived equal to the horizontal one). Finally the magnitude of the illusion is equally important for the 'L'-configuration and for the '+'-sign configuration and amounts to about 5% of illusion.

The magnitudes of the illusion were submitted to a repeated measure Analysis of Variance (ANOVA) with a between-subjects factor (*group*: patients *versus* control participants). On average, for control participants the anisotropy component ('*a*') corresponds to 5% of overestimation, whereas it corresponds to 11% of overestimation for neglect patients ($F(1,16) = 39.88$, $p < 0.0001$)) and 10% of overestimation for RH patients (RH-patients *versus* control participants: $F(1,16) = 37.4$, $p < 0.0001$). The bisecting component ('*b*') corresponds to 17% of overestimation for control participants and to 22% of overestimation for neglect patients ($F(1,16) = 35.37$, $p < 0.0001$)) and 20% of overestimation for RH patients (RH-patients *versus* control participants: $F(1,16) = 29.14$, $p < 0.001$). Patients show an increment, significantly larger from those found for control participants, for both parameters studied.

An alternative way to interpret the data is to transform the parameter '*a*' into a depth effect. If the length of the vertical line is overestimated because it is assumed to belong to a slanted plane, the perceived length equals approximately the physical length divided by the cosine of the slant angle. Following this reasoning, the magnitude of the illusion corresponds to a figure presented in a plane slanted by 18° for control participants, by 26° for neglect patients and by 25° for RH-patients.

The full model that describes the vertical–horizontal illusion contains three parameters; thanks to this model, sensitivity (represented by the uncertainty parameter, i.e., parameter '*c*') can be clearly separated from bias (represented by the anisotropy and bisection components). Neglect and RH-patients present shallower psychometric functions than controls (see Fig. 3), but this result has no influence on the analysis of the biases underlying the illusion. This uncertainty parameter, which is proportional to the uncertainty to estimate the length of a segment, equals to 0.10 for control participants, 0.26 for neglect patients and 0.20 for RH-patients.

The next analysis targeted more specifically a potential impairment of neglect patients to process those stimuli that were oriented to the left. We therefore focus here on the 'L' figures and on the horizontal-'T' stimuli. Fig. 4 shows the proportion of times control participants (on the left), N-patients (on the middle) and RH-patients (on the right) decided that the vertical segment was longer than the horizontal one, as a function of the aspect ratio of the stimulus. We split the data in four categories: (1) the 'L' oriented to the right (the horizontal segment is to the right of the vertical one; see Fig. 2, L1 and L2), (2) the horizontal-'T' oriented to the right (Fig. 2, T2), (3) the 'L' oriented to the left (Fig. 2, L3

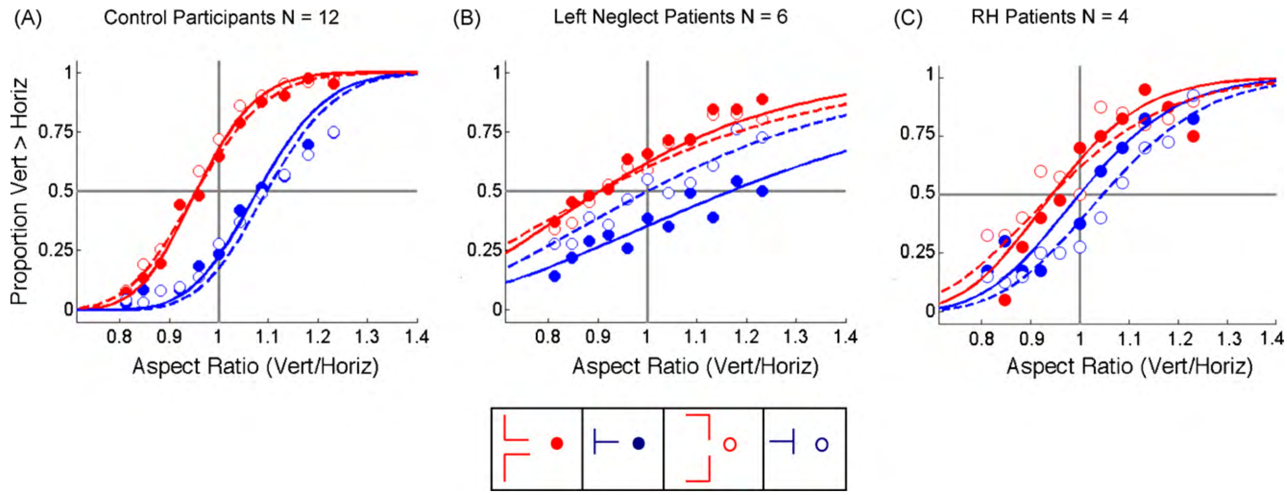

Fig. 4. Results for left and right oriented stimuli. The proportion of times the vertical segment was perceived longer than the horizontal one is shown against the aspect ratio of the figure for stimuli oriented to the left (open symbols) versus to the right (filled symbols), for the L-configuration (in red) and for the horizontal-T configuration (in blue). (A) Data for the control participants ($N = 12$), (B) data for the left neglect patients ($N = 6$) and (C) data for right brain damaged patients without neglect ($N = 4$).

and L4), and (4) the horizontal-'T' oriented to the left (Fig. 2, T4). We found no difference between stimuli oriented to the left and to the right for the 'L'-configurations, neither for control participants ($F(1,22) = 3.03$, $p = 0.10$, NS) nor for both groups of patients (neglect patients $F(1,10) = 1.53$, $p = 0.24$, NS; RH-patients $F(1,6) < 1$, NS). In contrast, there was a difference for the 'T'- configuration between stimuli oriented to the left *versus* to the right only for neglect patients ($F(1,10) = 5.40$, $p < 0.05$)) whereas we did not find any such difference for control participants ($F(1,22) < 1$, NS) and RH-patients ($F(1,6) < 1$, NS).

The difference found for the left and right oriented horizontal-'T' configurations was examined more precisely with the help of our model (Fig. 5). For this purpose, we split parameter '*b*' into three sub-components for each of the 'T' configurations of interest. First, '*b1*' corresponds to the bisecting parameter for the vertical-'T' configurations (both upright and inverted). Then, '*b2*' corresponds to the bisecting parameter for the horizontal-'T' configuration oriented to the right and '*b3*' to the horizontal-'T' oriented to the left. For control participants and RH-patients, there were no differences between these three sub-components (for control participants: $t_{b1-b2}(20) = 1.53$, $p = 0.22$, NS; $t_{b1-b3}(20) = 1.67$, $p = 0.21$, NS; and $t_{b2-b3}(20) = 2.24$, $p = 1.17$; for RH-patients: $t_{b1-b2}(20) = 1.24$, $p = 0.18$, NS; $t_{b1-b3}(20) = 1.92$, $p = 1.03$, NS; and $t_{b2-b3}(20) = 3.12$, $p = 0.09$). For neglect patients, there were still no differences between parameters '*b*1' and '*b2*' ($t_{b1-b2}(20) = 1.12$, $p = 0.32$)) and between parameters '*b*1' and '*b*3' ($t_{b1-b3}(20) = 2.24$, $p = 1.17$). However, as we expected, there was a difference between parameters '*b2*' and '*b3*' ($t_{b2-b3}(20) = 5.71$, $p < 0.05$). In other words, the bisecting parameters for the horizontal-'T' configuration oriented to the right and for the horizontal-'T' configuration oriented to the left were significantly different only for neglect patients.

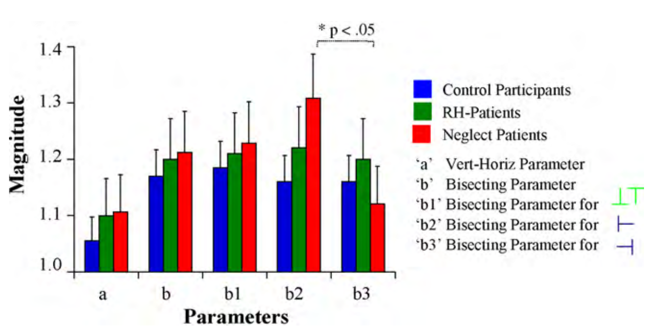

Fig. 5. Magnitude of the components of the illusion. We analyse the magnitude of parameter '*b*' (i.e., the bisecting parameter) for each T-configuration (the vertical-T, the horizontal-T oriented to the left and the horizontal-T oriented to the right) for control participants (in blue), neglect patients (in red) and right brain damaged patients with no neglect (in green). A significant difference was only found between the bisecting parameter '*b2*' (horizontal-T oriented to the right) and parameter '*b3*' (horizontal-T oriented to the left) for neglect patients ($t_{b2-b3}(20) = 5.71$, $p < 0.05$).

4. Discussion

The vertical–horizontal illusion is still poorly understood but it is now accepted that two parameters can explain why human beings have a tendency to overestimate vertical lines compared to horizontal ones of the same physical length (Künnapas, 1955). The first factor is a genuine anisotropy between vertical and horizontal segments, i.e., a bias to overestimate the vertical length. The second factor is a length bisection bias. According to this latter bias, a line that is bisected in two parts will appear shorter than if it were not interrupted. These two factors, orientation anisotropy and length bisection, provide a very good account of the magnitude of the illusion in various configurations of the illusion when the stimulus looks like a 'T', an 'L', or a '+'-sign, and for different stimulus orientations.

The anisotropy parameter was relatively small for both left neglect patients, right brain damaged patients without neglect and control participants (11, 10, and 5% of length mis-estimation) when it is compared to the bisecting parameter (22, 20, and 17%, respectively). Given that it is the anisotropy component that might be related to a 3D percept, this illusion might not be the best tool to investigate 3D perception in clinical cases. However, even if it turns out not to be a good tool to study 3D, it seems that the vertical–horizontal illusion could become a valuable test to investigate patients with little signs of left neglect.

Despite a large amount of research, there is still no clear consensus among clinicians regarding the methods of identifying neglect. Clinical tests of neglect have frequently been poor in terms of validation and standardisation. Bowen, McKenna, and Tallis (1999) found that the frequency of occurrence of neglect in patients with right brain damage ranged from 13 to 82%. The assessment method used was one of the main factors explaining the discrepancies between the different studies. In a recent work, Azouvi et al. (2002) investigated the sensitivity of different tests of neglect after a right hemisphere stroke. Their assessment battery includes several paper and pencil tests and they looked for related disorders such as anosognosia, extinction and personal neglect. They found that about 85% of subacute right hemisphere stroke patients presented at least some degree of unilateral neglect, which was considered as clinically significant (moderate to severe) in 36.2% of cases. The presence of neglect was task dependent. Tasks including a strong visual component were the most sensitive, and the automatic rightward orientation bias seemed to be the best indicator of unilateral neglect. However, several tests were more likely to uncover evidence of neglect than a single test. Their neuropsychological battery is one of the most used in clinical evaluation of neglect currently in France and other countries. But this battery has two disadvantages; first, it is very long and time is short when testing neglect during a simple neuropsychological evaluation. Furthermore, this battery is not sensitive enough for patients who present little signs of neglect. Our results are interesting in the sense that we find a difference for one configuration of the stimulus (the horizontal-'T' configuration, oriented to the left *versus* to the right) for neglect patients who showed little signs of neglect, and no difference for right brain damaged patients without neglect. Therefore, the horizontal-'T' configurations of the vertical–horizontal illusion might be a useful tool to diagnose the clinical population of neglect patients showing little signs of neglect.

The specific impairment of neglect patients for some stimuli and not others is better understood in the light of our model that distinguishes anisotropy and bisection components to the vertical–horizontal illusion (Mamassian & de Montalembert, 2010). More specifically, we found a doubling of the magnitude of the anisotropy component in neglect patients relative to controls. In contrast, the bisection parameter was overall moderately larger in patients than in controls, but there was a large difference for neglect patients on this bisection parameter for the horizontal-'T' configurations oriented to the left *versus* to the right. We offer two interpretations to explain this difference.

The first interpretation involves an attentional draw towards line junctions in an image. The way lines intersect each other in an image is critical for image understanding and to infer 3D properties from the 2D images (Barrow & Tenenbaum, 1981; Rubin, 2001). For instance, 'T'-junctions are often associated with the occlusion of an object by another one, where the boundary of the occluded object is the stem of the 'T'. Because of their primary importance to interpret a 3D scene, junctions presented in the image would attract the observer's attention. When the junction is on the right side of the figure, as it is the case in the left-oriented horizontal-'T' stimulus, neglect patients might have a difficulty to disengage their attention from the junction to properly evaluate the distance to the end-point of the horizontal segment. Such a deficit of neglect patients to disengage their attention from right to left has been reported in the literature (Bartolomeo & Chorkon, 1999; Posner, Walker, Friedrich, & Rafal, 1984). It could also be a kind of ipsilesional hyperattention, because contralesional stimuli are not strictly unnoticed. Nevertheless, we supposed that the reason why 'L' figures oriented to the left do not trigger the same deficit might be that in these figures, the intersection is a degenerated junction and thus attracts attention less strongly.

The second interpretation involves the saliency of the horizontal segment and its strength in affecting the length judgment of the vertical line it bisects. When we analyzed the performance of neglect patients in the light of our model, we found that neglect patients presented a significant difference in the value of the bisection parameter for the horizontal-'T' configurations between the left and right oriented figures. The magnitude of the bisection parameter represents an under-estimation of the length of the bisected line. A difference in magnitude of this parameter may be interpreted as a difference in saliency between the bisecting and the bisected line: a highly salient bisecting line may increase the magnitude of the length bias, and reversely a highly salient bisected line may decrease its magnitude. Following this reasoning, a smaller magnitude of the bisection parameter for the horizontal-'T' oriented to the left would indicate that neglect patients perceive the horizontal line with the appropriate length but that their representation of this line is too weak to have a very strong bisection effect on the vertical line. In contrast, when the horizontal-'T' is oriented to the right, the vertical line is less salient than the horizontal one, and the magnitude of the bisection effect increases. The reason why 'L' figures oriented to the left do not trigger the same deficit is very different from the previous interpretation. According to the second interpretation, 'L' figures do not present a different perception than controls simply because these figures are not subject to the bisection component of the illusion.

In summary, neglect patients differ from right brain damaged patients and control observers in the vertical–horizontal illusion only on very specific aspects of the illusion. In particular, neglect patients are not only different from controls when it comes to compare the length of lines at different orientations but they are behaving differently depending on the spatial configuration of the two lines. In addition, the effects reported here are robust and as such might be useful to detect even mild forms of neglect.

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