Original Research Article

Bidimensional spatial distortion in quadrantanopia depends on the cortical damage and not on the deprived region in the visual field

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ABSTRACT

:
Aims: To assess whether the spatial distortion underlying the so-called “thin man phenomenon” experienced by cortically impaired patients with homonymous defects depends on the cortical damage or on the scotoma itself.
Study Design: Analysis of a representative case.
Place and Duration of the Study: Service of Neuro-Ophthalmology, University of Turin, Italy, from January 2017 to July 2017**.**
Methodology: Spatial relationship perception, that is the function able to discriminate the extent of a shape along the cardinal coordinates, has been estimated in the visual field of a patient with left inferior quadrantanopia due to cerebral stroke at different eccentricities. The threshold as a function of the distance from the border of the scotoma was compared with two normal subjects after the same defect has been simulated.
Results: Spatial relationship perception was not affected by the simulated scotoma in the normal subjects, as shown by the lack of correlation between this variable and the distance from the upper border vs the nasal border of the deprived region. On the contrary, in the patient spatial relationship perception was anisotropic close to the boundary of the scotoma, and the effect decreased as a function of the distance from the blind region (R^2=0.77, *P*: .04).
Conclusion: This finding suggests that the cortical impairment and not the scotoma itself is responsible for the spatial distortion in presence of homonymous visual field defects.

Keywords: Stroke; Quadrantanopia; Visual Distortion; Spatial Relationship Perception; Thin Man Phenomenon, Anisotropy.

1. INTRODUCTION

In evaluating the integrity of the visual field after cerebral accidents, the degree of perceptual impairment is judged as a function of the width and depth of the perimetric loss. So, within the clinical practice, hemianopic or quadrantanopic patients are defined as those suffering from binocular loss of vision in correspondent half or quadrants of their visual field. On the contrary, the function in the contralateral (spared) regions is considered intact. Yet, even if differential light sensitivity (as measured by perimetric testing) is within the normative range, studies show that in some respects abnormal perception is likely to affect even the spared visual field. For example, delay in visual categorization and detection has been reported in the (presumably) intact central visual field of left and right hemianopic patients [1]. An abnormal function would not be limited to a sluggish response to a visual stimulus but involves the retinocortical mapping. Indeed, in hemianopia spatial distortion has been documented close to the borders of the scotoma. Such distortion would explain the occurrence of the so-called Hemianopic Line Bisection Error (HLBE), that is the bisection of lines biased toward the blind hemifield (see for example [2-5]), or an illusory shorter perception of lines crossing a scotoma of cortical origin [6].

There is evidence that in presence of visual field defects of cortical origin the perceptual distortion is not restricted to a single spatial dimension, but extends to more complex, bidimensional configurations: as a matter of fact, patients with small paracentral homonymous scotomas or showing a quadrantanopia are reported to perceive the face of their interlocutors as smaller and thinner on the side of the scotoma (the so-called "thin man phenomenon" [7-10]; moreover, systematic overestimation of the height of rectangles presented close to the border of a quadrantanopia has been documented by Dilks et al [11]. A solution for this (bidimensional) spatial distortion has been provided by the authors in terms of a perceptual “stretch” of the proximal stimulus towards the scotoma: the stretch would be due to a reorganization of the receptive fields in the spared regions of the visual space [7,8,10].

Arguably, the perceptual “stretch” responsible for these cases of dysmorphopsia can be explained in terms of abnormal spatial relationship perception. We have defined spatial relationship perception (SRP) as the visual function able to discriminate the different extent of a shape, namely of an ellipse, along the vertical and horizontal coordinates (i.e. the aspect ratio [12]). The minimum difference between the vertical and horizontal focal axis needed to discriminate an ellipse from a circle reflects the spatial relationship sensibility along the y- and x-coordinates, respectively [13]: so, spatial relationship anisotropy (SRA) can be estimated as the difference in spatial relationship sensibility along the two cardinal references. Dilks et al studied the visual distortion close to a quadrantanopia in a patient suffering from stroke and found that at the point of subjective equivalence vertical rectangles were perceived as equal in height when rectangles on the side of the scotoma were 3 degrees shorter than the ones presented in the contralateral quadrant. This spatial relationship anisotropy confirms the existence of a spatial distortion close to the nonresponsive region, and has been explained by the authors in terms of cortical reorganization: the deafferented area of the striate cortex, corresponding to the scotoma, would acquire responsiveness to the surrounding regions, so that a stimulus adjoining the blind area will activate both the corresponding cortical area and the deafferented region. As a result of this double activation, the stimulus will be perceived as spatially “stretched” toward the nonresponsive region [11].

Within this framework a question arises whether abnormal SRA leading to spatial distortion depends on the immediate and reversible functional reorganization of the receptive fields in response to localized visual deprivation (i.e. it is a direct consequence of the scotoma itself [3,14]), or if it is directly related to a cortical damage and requires long-term adaptation [2,5,15,16]. In effect, on the one hand spatial distortion is shown to occur also in presence of an artificial scotoma [3] as well as around the blind spot [17,18] (i.e. with no need of cortical damage), on the other hand it has been documented after cortical impairment but in absence of an evident perimetric defect [9,15]. According to this last evidence, therefore, a visual distortion would occur only if a cerebral lesion inducing a cortical reorganization takes place, whereas the presence of a well detectable scotoma would not be a necessary condition.

To shed light on this issue, in this paper spatial relationship perception, namely abnormal spatial relationship anisotropy, has been measured in a patient suffering from homonymous quadrantanopia due to occipital stroke at different distances from the borders of the scotoma. Interestingly, she complained of a slightly distorted perception close to the blind region, a symptom suggestive of dysmorphopsia. Results have been compared with those obtained in two normal subjects after the same perimetric defect has been simulated.

According to our working hypothesis, increased SRA at the borders of the pathological scotoma and normal SRA close to the simulated area of visual deprivation will support the hypothesis that an occipital brain injury is necessary for the occurrence of the spatial distortion responsible for the thin man phenomenon. Otherwise, the theory that the spatial distortion is a direct consequence of the scotoma itself will gain evidence.

2. METHODOLOGY

2.1 Spatial Relationship Perception

Spatial relationship perception has been assessed by using the paradigm described in a previous investigation [13]. In brief, the test is performed on a flat LCD 15” screen and makes use of a staircase psychophysical algorithm (accelerated stochastic approximation [19]) to estimate the discrimination threshold between circles and ellipses horizontally- or vertically-oriented. Trial after trial the observer was required to identify the stimulus (2.8 deg wide) either as a circle or as a horizontal or vertical ellipse, according to a three alternative forced choice response procedure (3AFC).

The threshold is expressed as Interaxis Ratio (IR), that is the percent difference between the focal axis *fa* and the perpendicular axis *pa* of the elliptical stimuli, according to the formula:

$$IR\ (\%) = 100\ [fa(x,y) - pa(y,x)]\ /\ fa(x,y)$$

Evidently, the smallest *fa(x,y) – pa(y,x)* that makes an ellipse barely recognizable reflects the spatial relationship sensitivity of the subject under examination. Under this perspective, we consider the visual system as isotropic if the spatial relationship sensitivity is the same along the horizontal and vertical axis (i.e. if SRP is independent of the stimulus orientation: *fa(x) – pa(x) = fa(y) – pa(y)*). Otherwise, spatial relationship anisotropy (SRA) takes place, and its amount is computed as the difference between the discrimination threshold along the x, y cardinal axis (Horizontal Threshold, HT and Vertical Threshold, VT, respectively). The test assesses HT and VT independently by using two interleaved tracks.

Spatial relationship perception has been measured at a distance of 2,4,6,8, and 10 degrees from the superior boundary of the blind quadrant, 6 deg from the vertical meridian passing through the fixation point. In addition, it has been estimated 2,4,6, and 8 degrees from the nasal boundary of the quadrantanopic defect, 6 deg from the horizontal meridian passing through the fixation point.

To compare the effect of the scotoma on spatial relationship perception, the corresponding loci in the contralateral upper quadrant have been tested according to the same modality. The estimation of HT and VT in the selected loci was randomized, as it occurs in conventional perimetry.

The thresholds obtained in the two spared adjoining quadrants have been compared with the references estimated at the corresponding loci in the right superior quadrant (figure 1).

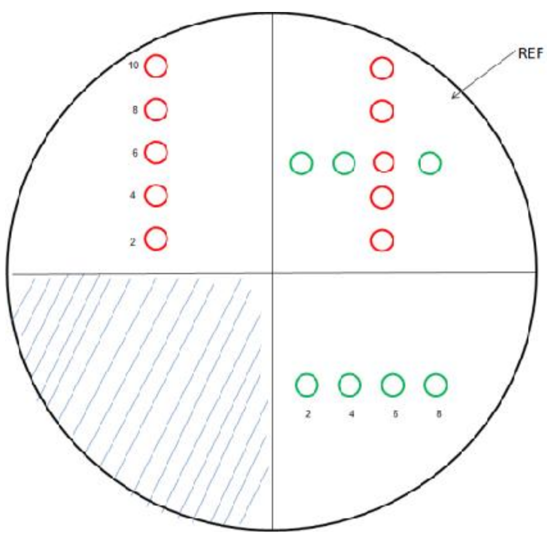

Fig. 1. Locations of SRP estimates in the three spared quadrants

In addition to the within-individual comparison, a between-individual comparison has been performed relative to the normalized threshold functions obtained in the two patients and the correspondent normalized functions measured in two normal observers. In order to make the perceptual condition of the two normal subjects as much like that of the patient (including the risk of unstable fixation as a potential drawback able to reduce the precision of the threshold estimate in the latter) in the two controls left inferior quadrantanopia has been simulated by applying a triangular sector made of black paper to the inferior left portion of the lenses of a pair of glasses. Before starting the examination the operator made sure the lenses with the sector were as close as possible to the eye of the subject. To obtain confirmation that this way a left inferior quadrantanopia was correctly simulated, a preliminary binocular visual field was performed using kinetic perimetry [20] before the subject underwent the experimental session.

The observer sat on a chair with the head firmly placed on a chinrest 60 cm from the monitor. She was asked to look steadily at a fixation cross in the center of the monitor. Fixation stability was continuously monitored by the operator. In case of fixation loss, the session was discarded and repeated a few minutes later. The illuminance of the dimmed room chosen for the experiments was 0.15 lux.

2.2 Subjects

Two normal subjects (the co-author FP, and SF, females, age 24) and a 74 years old woman affected from an absolute and well localized post-stroke perimetric defect involving the entire left inferior temporal quadrant of the visual field were examined. The two control subjects did not suffer from any ophthalmological as well as systemic disease, and their natural visual acuity was 60/60.

In the patient the ischemic lesion involved the gray and white matter of the left occipital lobe. The quadrantanopia was confirmed by using the Humphrey visual field analyzer (program 30-2). The patient, who did not suffer from cognitive deterioration, was pseudophakic and her visual acuity was 60/60 (right eye: no correction, left eye: mild astigmatism) in absence of other ophthalmological diseases like glaucoma or age-related macular degeneration. Her fixation was stable.

After preliminary ophthalmological and orthoptic examination, spatial relationship perception was tested in the two simulated conditions of quadrantanopia, as well as in the real case. The operator FP conducted the experiment in a darkened room (illuminance: 0.15 lux).

The two authors hereby declare that the experiment has been examined and approved by the ethics committee and has therefore been performed in accordance with the ethical standards laid down in the 1964 declaration of Helsinki. Informed consent for publication was obtained from the subjects who underwent the experiment after explanation of the aims of the study.

3. RESULTS

In table 1 the HT and VT estimates in the three spared quadrants of the visual field of subject FP are reported. Spatial relationship perception along the x/y axis in the quadrants adjoining the simulated scotoma and in the reference region was similar (HT: Kruskal-Wallis, KW: 0.77, P=.67; VT: KW:0.16; P=.92). The amount of anisotropy, expressed by the difference between the sensitivity along the vertical and the horizontal meridian, is negligible (and comparable to the normal population [13]).

Table 1. Spatial relationship threshold along the x- and y-axis in the three quadrants. Subject FP

Quadrant	HT median (IQR)	VT median (IQR)
SUP TEMP	4 (4)	4 (5.5)
INF NAS	2.5 (3.5)	5.5 (5)
SUP NAS (reference)	3 (3.25)	6 (2.25)

Figure 2 depicts SRP as a function of the distance from the occluded region and from the horizontal midline in the reference quadrant. No correlation was found between spatial relationship sensitivity along the vertical as well as the horizontal coordinate and the distance from the simulated blind quadrant (Pearson R^2= 0.22, P= .41 and R^2= 0.05, P= .69).

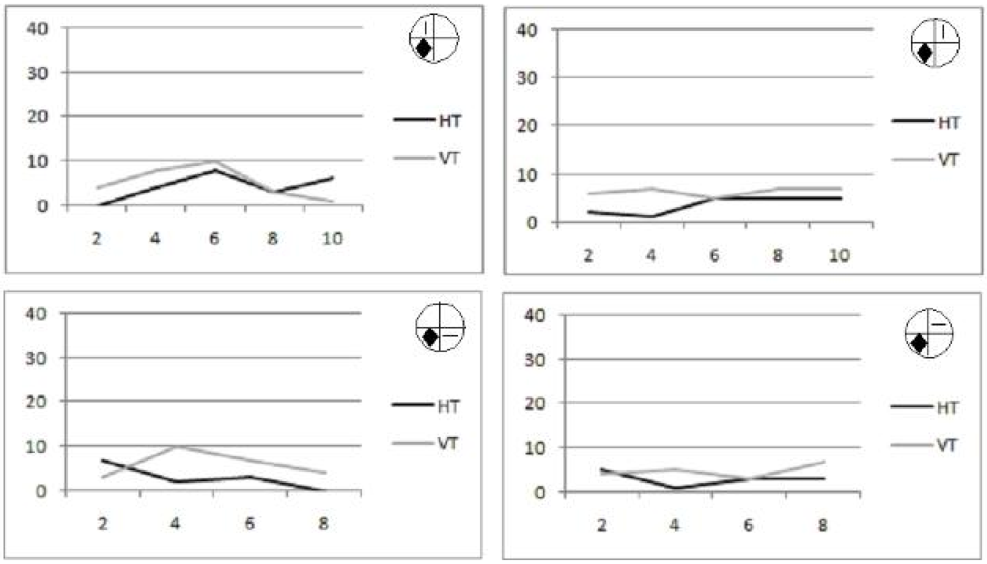

Fig. 2. Threshold referred to spatial relationship perception as a function of the distance from the simulated blind region of subject FP
Right panels: references

In summary, in subject FP spatial relationship perception is substantially constant across the central visual field and is not affected by a simulated quadrantanopic defect.

In subject SF, too, spatial relationship threshold along the y-axis did not differ in the quadrants adjoining the simulated scotoma compared to the reference region (Kruskal-Wallis, KW: 3.98, *P*=.13). On the contrary, the horizontal threshold in the superior temporal quadrant was higher compared to the reference region of the visual field (Kruskal-Wallis, KW: 7.70, *P*= .02; table 2).

Table 2. Spatial relationship threshold along the x- and y-axis in the three quadrants. Subject SF.

Quadrant	HT median (IQR)	VT median (IQR)
SUP TEMP	10 (1.75)	1 (2.25)
INF NAS	8 (3.5)	1.5 (4)
SUP NAS (reference)	6 (2)	6 (3)

Like in subject 1, no correlation was found between spatial relationship sensitivity along the vertical as well as the horizontal coordinate and the distance from the simulated blind quadrant (Pearson R^2= 0.03, P= .75 and R^2= 0.12, *P*= .55: figure 3). In this case, too, the amount of anisotropy in the superior temporal quadrant is not influenced by the proximity of the simulated scotoma (Pearson R^2=0.45, *P*= .21).

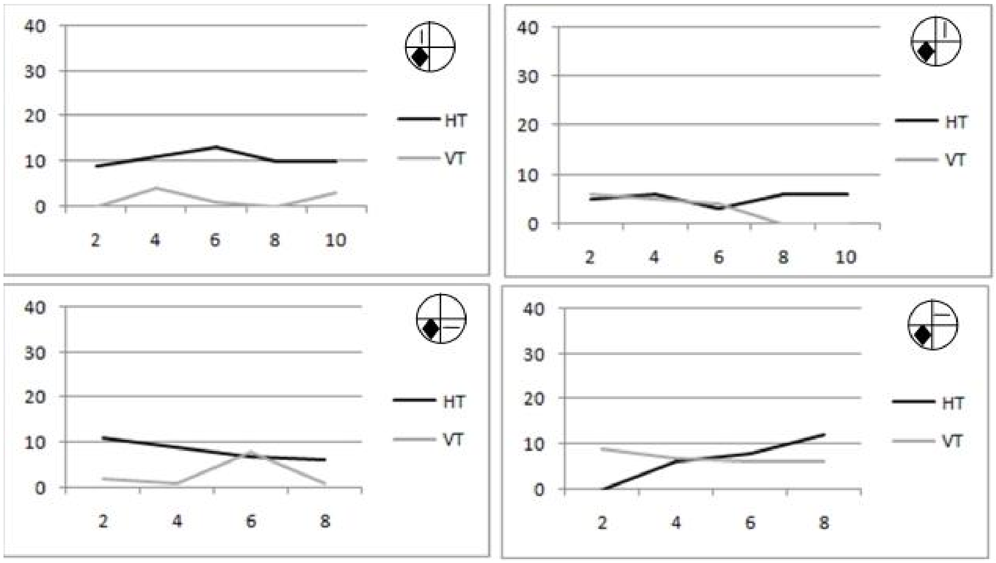

Fig. 3. Threshold referred to spatial relationship perception as a function of the distance from the simulated blind region of subject SF.
Right panels: references

In summary, in subject 2 spatial relationship perception along the vertical coordinate is substantially constant across the central visual field. Despite the quadrants adjoining the simulated scotoma showed lower sensitivity along the horizontal axis compared to the reference region, the lack of correlation between spatial relationship sensitivity and distance from the border of the deprivation area does not support the putative influence of the latter on the former.

As shown in table 3, spatial relationship sensibility of the patient was lower compared to the two controls. Even if the averaged vertical threshold was higher in the two quadrants adjoining the scotoma compared to the reference quadrant, such difference did not reach statistical significance (Kruskal-Wallis, KW: 0.96, P=.61). On the contrary, the median horizontal threshold was higher in the superior temporal quadrant compared to the reference (Kruskal-Wallis, KW: 6.7, P=.03).

Table 3. Spatial relationship threshold along the x- and y-axis in the three quadrants in the quadrantanopic patient.

Quadrant	HT median (IQR)	VT median (IQR)
SUPTEMP	19 (3.25)	17 (6)
INF NAS	13.5 (7)	15.5 (6)
SUP NAS (reference)	15 (2.25)	14 (4.25)

By inspecting figure 4, a difference can be noted between the horizontal and the vertical threshold in the two quadrants close to the border of the scotoma (panels a and c, 2 deg from the deprived area), but not in the reference quadrant (panels b and d). Spatial relationship sensitivity, in fact, is lower along the horizontal and higher along the vertical coordinate (i.e: higher threshold along the horizontal, lower threshold along the vertical) in the ipsilateral superior quadrant, while the opposite takes place in the contralateral inferior region. Such anisotropy tends to disappear as the distance from the boundary of the blind region increases (Pearson: R2=0.77, P=.04); since it does not take place in the reference region, it could be argued the blind region of the visual field affects spatial relationship perception across the neighboring visual space (panel e).

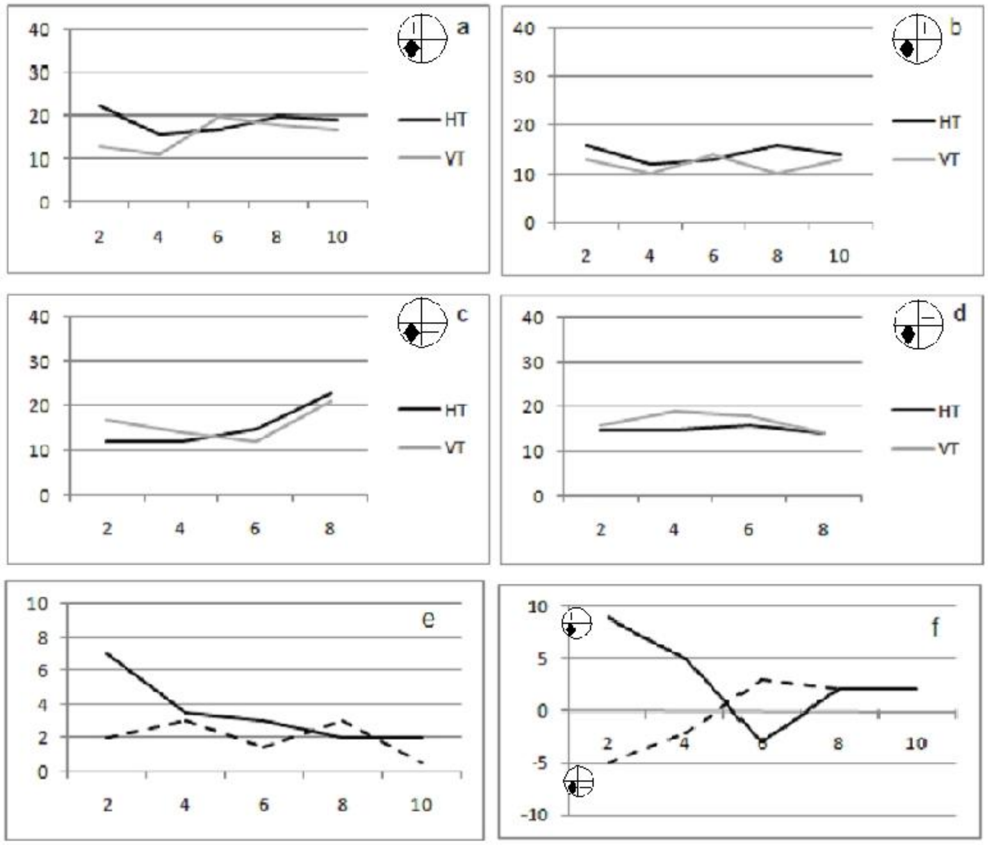

Fig. 4. Threshold referred to spatial relationship perception as a function of the distance from the blind region of the quadrantanopic patient. Panel e: overall SRA as a function of the distance from the border of the scotoma (continuous line), and, as a reference, from the vertical meridian crossing the fixation point in the upper nasal quadrant (dashed line). Panel f: SRA as a function of the distance from the border of the scotoma in the superotemporal (continuous line) and inferonasal quadrant (dashed line).

The direction of the anisotropy is opposite in the upper vs the nasal side of the scotoma: in the upper region the sensitivity is higher along the vertical axis, whereas in the nasal region it is better along the horizontal axis. In both cases the perceptual unbalancing tends toward isotropy the farther away from the blind region, with a ceiling effect at about 6 deg (panel f).

4. DISCUSSION

There is evidence that perceptual distortion occurs at the borders of a scotoma [e.g.: 4-6] and, at least at a higher (bidimensional) level, it is stated to take place in presence of a posterior cerebral damage [7-11].

Indeed, the spatial distortion like the thin man phenomenon experienced by patients with homonymous defects due to occipital stroke would depend on a neuronal network reorganization in the visual area correspondent to the affected visual field: such reorganization would consist of axonal sprouting of horizontal cells and disinhibition of long-range horizontal connections [6,21]. Yet, alongside these permanent cellular changes, rapid and reversible cortical reorganization responsible for similar (even if monodimensional) perceptual bias has been reported by Kapadia et al close to an artificial scotoma made of a dynamic random dot field [22], and by Mitra et al, [3] and Ogun et al [14] in presence of a simulated homonymous hemianopia.

Based on these findings, it remains unclear if a scotoma is sufficient to generate a consistent spatial distortion or if the spatial distortion is most strictly related to a cortical damage. Mitra estimated the occurrence of the line bisection error in normal subjects with simulated homonymous hemianopia and concluded that the visual field defect itself is enough to determine the bisection bias, irrespective of the presence of a cortical damage [3]. A similar result has been confirmed by Ogun et al [14].

On the contrary, Zihl et al studied the bisection error in 84 patients suffering from homonymous hemianopia and stated that the bias is not the consequence of the visual field defect, but depends on an injury in the occipital-temporal areas [2]. The same conclusion has been given by Schuett et al. [16].

In this paper, bidimensional spatial distortion in a patient suffering from post-stroke quadrantanopia and in corresponding conditions simulated in two normal subjects has been assessed in terms of spatial relationship perception. The simulated quadrantanopia did not seem to affect spatial relationship perception in the two normal subjects: In fact, it was substantially constant across the central visual field with a mild degree of anisotropy, well within the normality range as estimated in our previous study [13].

These findings are in contrast with the line bisection error described in simulated hemianopia by Mitra et al [3] and Ogun et al [14]. Still, it should be noted that in subject SF the sensibility along the horizontal meridian was lower in the quadrants adjoining the occluded region. Even if this finding is controversial (the threshold does not decrease as a function of the distance from the scotoma), it seems to indirectly support the monodimensional distortion found by the abovementioned authors in their simulated cases. Yet, it remains that the isotropy of the visual space is not afffected by the scotoma itself in absence of a cortical damage.

It cannot be ruled out that if a monodimensional bias may occur in absence of cerebral lesion and may involve short-term and reversible functional reorganization (despite Zihl et al are in disagreement with this solution [2]), a more complex, bidimensional distortion may require occipital cortical damage and permanent anatomical strengthening of the horizontal axonal connections [21]. As a matter of fact, the detection of a difference in the extent of stimuli along the cartesian axis is substantially a different task from the line bisection, and presumably requires more radical changes in the cortical cytoarchitecture than those caused by the temporary occlusion of a portion of the visual field.

Contrary to the simulated conditions, in the quadrantanopic patient affected by occipital stroke visual distortion takes place near the deprived area. Indeed, her visual perception was anisotropic close to the border of the scotoma and tended toward isotropy the farther away from the blind region.

The direction of the anisotropy is consistent with previous studies showing a shift of the visual space toward the scotoma [7,8,11]. In the region close to the superior border of the blind region the threshold along the y-axis is consistently lower than along the x-axis, determining a perceptual vertical dilation and horizontal contraction. On the contrary, in the quadrant adjacent to the nasal border of the blind region the threshold along the x-axis is consistently lower than along the y-axis, determining a perceptual horizontal dilation and vertical contraction. As a result, circular stimuli are misperceived as vertical ellipses on the superior side of the scotoma, and as horizontal ellipses on the nasal region (figure 5).

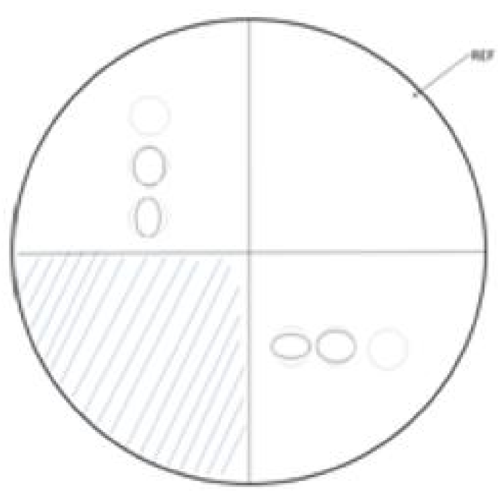

Fig. 5. Simulated misperception as a result of the illusory "stretching" of the visual space toward the scotomatous region. Presented stimuli: grey circles; perceived stimuli: black ellipses. See text for explanation.

Our result supports the finding of Fortenbaugh et al, who discovered selective horizontal expansion of the visual space close to the boundary of the quandrantanopic area in two cases of left and right hemianopia [4]. Accordingly, the vertical and horizontal components of the size distortion were reported to be differently affected in a subject with right prestriate lesion [15]. This selective distortion of the visual space may, therefore, account for the perceptual stretching suggested to be responsible for the “thin man phenomenon” described by Safran et al. The strengthening of the long-range horizontal projections in the visual cortex (leading to enlargement of the receptive fields close to the deafferentiated area, see for example: [23, 24]), would account for the perceptual shift toward the scotoma [6], and would be achieved via synaptogenesis and by axonal sprouting [21].

Interestingly, in our patient anisotropy decreased as a function of the distance from the border of the scotoma up to about 6-8 degrees of eccentricity from the deprived region, then it showed a ceiling effect and no further increase was observed. Maybe this spatial interval reflects the spatial extent of the cortical reorganization and, more specifically, of the horizontal axonal sprouting on the cortex.

5. CONCLUSION

In conclusion, our preliminary report supports the hypothesis that spatial relationship anisotropy presumably responsible for the bidimensional visual distortion occurs in the presence of a cortical damage, whereas the associated region of spatial deprivation in the visual field per se does not appear to be substantial. The structural changes on the striate/peristriate area would affect the retinotopic map up to a distance corresponding to 6-8 degrees from the border of the scotoma. Further investigations are needed to study the characteristics of cortical plasticity in the presence of visual field defects of cortical origin, and to understand the way it can be used to improve the visual function of patients suffering from cerebral accidents.

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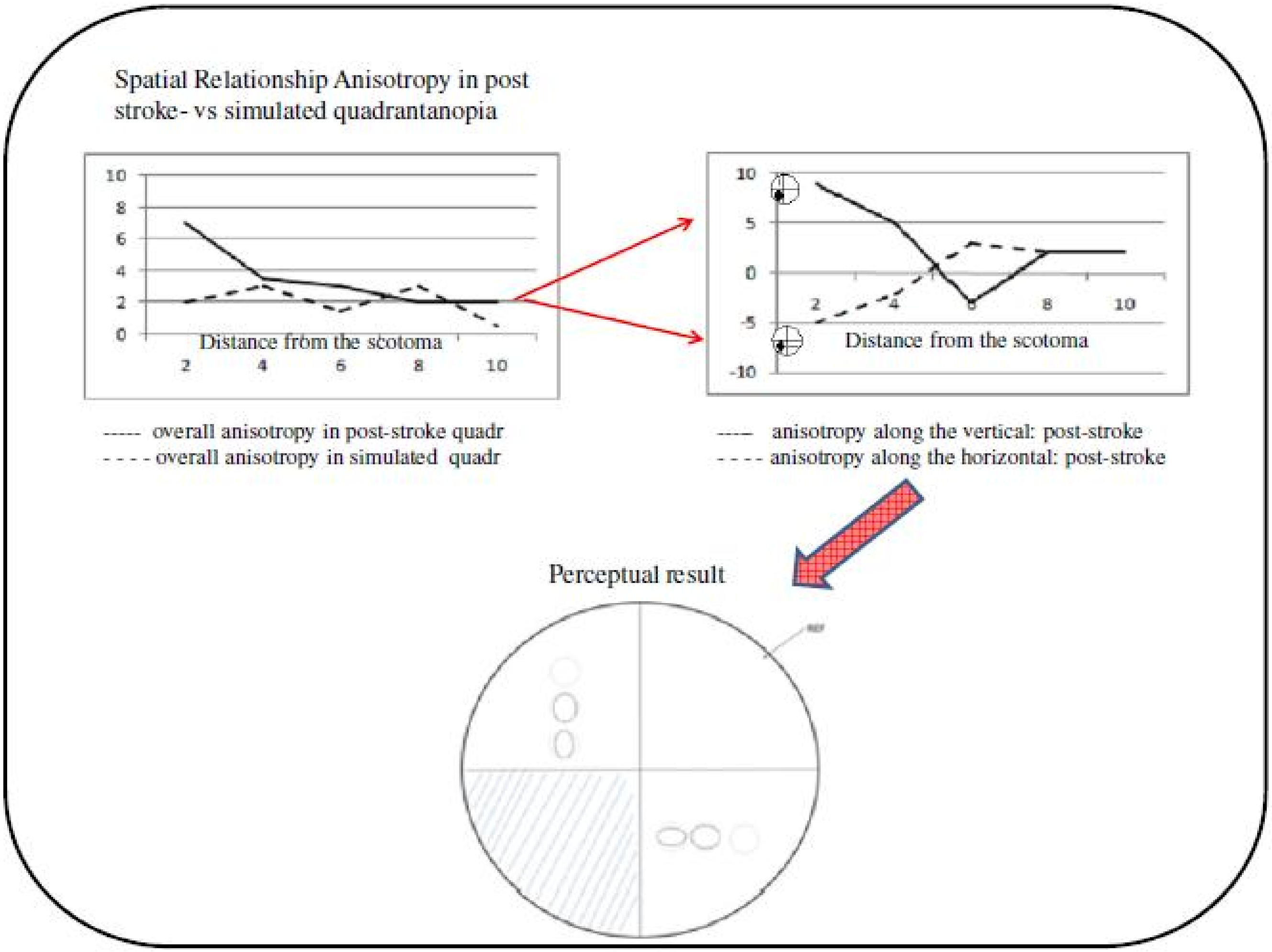
Spatial Relationship Anisotropy in post stroke- vs simulated quadrantanopia
Distance from the scotoma
----- overall anisotropy in post-stroke quadr
- - - - overall anisotropy in simulated quadr
Distance from the scotoma
---- anisotropy along the vertical: post-stroke
- - - - anisotropy along the horizontal: post-stroke
Perceptual result