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STEREOSCOPIC DEPTH PERCEPTION IN PERIPHERAL FIELD AND GLOBAL PROCESSING OF HORIZONTAL DISPARITY GRADIENT PATTERN

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ABSTRACT. This study investigated how the visual system detects a surface deviation from planar, induced by, crossed or uncrossed, horizontal disparities continuously increasing with eccentricity. Binocular disparities increased linearly and concentrically, between two given eccentricities. The thresholds of deformation detection were gathered using a method in which observers halted a dynamic stimulus. The thresholds were substantially higher than those measured by the control experiment using a method of constant stimuli. Results, using the adjustment method, highlighted lower discrimination thresholds for uncrossed disparities than for crossed disparities. For all the directions of disparity, thresholds varied similarly as a function of eccentricity, however two observations could be pointed out: thresholds of peripheral start depended on disparity gradient and starting eccentricity; fovea start thresholds did not depend on disparity gradient alone. Data suggests that, in peripheral field, the visual system was more sensitive to uncrossed disparities than crossed disparities, relative to the frontoparallel plane. According to a verbal report from observers, the reference used for the perceptive judgment appears not to be the screen plane but rather the peripheral stimulus. Moreover, in the deformation detection of planar surfaces, horizontal disparities processing depends on the eccentric location of the disparities. It could be global for the peripheral locations and could be based more on depth contrast for the central locations.

Key words: horizontal disparity, surface perception, disparity gradient, perceived depth, eccentricity, deformation.

INTRODUCTION

In the present study, we investigated the human ability to discriminate the sign of deviation from planar surface as a function of disparity gradient located at different eccentricities. Stereoscopic depth can be perceived beyond 30° of eccentricity, it is known that horizontal disparity sensitivity decreases with increasing eccentricity (Rawlings & Shipley, 1969) and with decreasing observation distance. Nevertheless, characteristics beyond the peri-foveal area were essentially studied for the perception of frontoparallel planes and to determine the position of the horopter as a

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function of various criteria: i.e. zero binocular disparity, zero deviation from equal perceived distance from the observer, or binocular fusion (Ogle, 1950; Tyler, 1983; Bourdy, 1989; Tyler, 1991). For the perception of frontoparallel planes behind or in front of the fixation point, Drobe and Monot (1997) found that apparent frontoparallel planes present curvatures depending on the relative distance in depth to the fixation point and these curvatures are similar to the ones observed for horopter shapes. The perception of planar surface and the conditions such that surfaces are perceived as planes were largely studied. However, little is known about patterns of crossed and uncrossed disparity variations that can elicit the perception of non planar surface in the peripheral visual field.

Continuous disparity variations such as horizontal gradients, applied to the whole figure, are poorly perceived in depth (McKee, 1983). The author's explanation was that continuous variations can constitute a powerful input for global fusion mechanism which would average disparities of different elements in order to obtain a mean depth value for the whole figure. Mitchison and McKee (1990) also explained this poor sensitivity to disparity gradients by the fact that depth is judged in relation to a reference plane. This observation was for gradients all along the figure, but is it true when the disparity gradients were concentrically or sinosoidally applied: gradients also occured on the whole figure, but there is a central point or lines of null disparity, and then some kinds of disparity gradient discontinuity. Mitchison and Westheimer (1984) suggested that the visual system uses the salience to determine which points are coplanar (equal saliences) in a visual scene and to detect corners (discontinuity of disparity gradient) between planes. The authors introduced the concept of salience of a visual object, which is the sum of weighted disparity differences between a visual object and its neighbours, to account for the depth perception. The weighting would vary inversely with distance in the frontal plane, i.e. eccentricity. Therefore detection of disparity gradient discontinuity could probably be based on disparity differences and could depend on eccentricity.

In addition to the concept of salience, some authors have shown that large variations in horizontal disparities allow to detect edges or boundaries: The stereoscopic system processes edges of surfaces, or discontinuities of disparity, more quickly and more precisely than a constant disparity gradient applied to the whole surface (Gillam, Flagg & Finlay, 1984). Slanted or inclined planes are produced by disparity gradient, whereas extreme curvatures can be considered as edges or boundaries of surfaces. Rogers and Cagenello (1989) then found that the visual system is more precise and more sensitive to surface curvatures than to slanted surfaces. Lunn and Morgan (1997) reported that performance in slant discrimination does not improve with a discontinuity of disparity gradient. Nevertheless, the authors added that stereoscopic vision is more sensitive to relative disparity than to disparity gradient. With a horizontal disparity gradient concentrically applied on a disc or ring-shaped surface, Devisme, Monot, Drobe and Pédrono (2004) showed that detection thresholds of concave deformation (using crossed disparities) of a frontoparallel plane depended on the disparity gradient and on the eccentricity from which it is applied. Therefore, in this specific layout of disparity gradient, to detect depth deformation, the visual system could process the disparity gradient difference and not the disparity difference between the central point (or disc) and peripheral areas.

According to Mitchison and McKee (1990), to make relative depth judgement between several objects, the visual system would also need a reference. The presence of a reference plane affected depth increment thresholds and improved relative depth judgement (Glennerster & McKee, 1999; Andrews, Glennerster & Parker, 2001). The authors suggested that the visual system might construct a reference plane for comparing disparities. Therefore, the sensitivity of the human stereoscopic system has been shown to depend on the distance of points with respect to a local reference plane. This reference plane could be defined by distant points, it could be distinct from the fixation plane and it could be slanted (Glennerster, McKee & Birch, 2002; Petrov & Glennerster, 2004; Glennerster & McKee, 2004). This processing avoids rebuilding a complex 3D-space for each eye- or head-movement, in eyecentric or headcentric coordinates. According to the work of Van den Enden and Spekreijse (1989), stereoscopic depth is also influenced by texture perspective. They showed that binocular depth reversal can be observed despite familiarity cues providing that the effect of texture perspective is neutralized. It could be said that the surface which is defined by the perspective cue can be considered as a reference surface for the processing of binocular disparity. Thus, disparity gradient applied to the whole field seems to be globally processed. Using the stimulus itself as the reference plane, the visual system would poorly detect constant disparity gradient.

The aim of the present study is to define the role of horizontal disparity in the perception of planar surface deviation over a large visual field, whatever the horizontal disparity direction is. In this experiment, we introduced horizontal disparity gradients (crossed and uncrossed disparity), between two eccentricities, in a frontoparallel plane, and measured the resulting detection thresholds of surface deformations (respectively convex and concave). The results showed difference in thresholds between crossed and uncrossed disparity in discrimination of surface deformation, and different behaviors between foveal and peripheral area.

EXPERIMENT

DESIGN AND PROCEDURE. The method used to determine thresholds for surface deformation discrimination was an intermediate method between ascending limits and ascending adjustment: one measurement consisted of the successive presentation of images with increasing level of disparity gradient at a fixed location. The observer did not really adjust the level of disparity gradient at his threshold, but he stopped the unwinding of images, i.e. the disparity gradient increasing, when he detected a depth change (Figure 2). The method of ascending adjustment usually gives thresholds higher than forced choice method, because of the progressive introduction of disparities. The choice of this method was because it permitted to collect many results on a lot of data (the experimental conditions with 18 different measurements were described below) and because the aim of this study was to investigate the variation of the thresholds, as a function of different parameters. A forced choice method was also used to control if observers perceived deformation in the correct direction (concave or convex) related to the direction of the disparities.

Binocular disparities were introduced by adding equal and opposite horizontal shifts locally to the image of each eye. Disparity was added to the frontoparallel plane, which already contains disparity. The frontoparallel screen plane is different from the horopter, and then it presents uncrossed disparities that increased with eccentricity. In the present experiment, null disparity meant points of the screen plane. The applied disparities increased concentrically between a first circle of eccentricity a and a second circle of eccentricity b (Figure 1) (a was called the eccentricity of the beginning of disparity variation, and b the eccentricity of the end of disparity variation). Eccentricity a values were: 0, 7 or 14° and eccentricity b values: 7, 14, 21, 28 and 35°. The nine tested pairs of eccentricity were: (0,7); (0,14); (0,21); (7,14); (7,21); (7,28); (14,21); (14,28); (14,35). Pairs (a,b) were randomly presented. Disparity value in the peripheral zone (beyond eccentricity b) was constant and equal to the value at the points on the circle of radius b. Therefore, disparity gradient discontinuities are induced on two concentric circles of radius a (reduced to a single point for a = 0) and b, separating an annulus of constant concentric disparity variation. The disparity variation, or disparity gradient, corresponded to the ratio $\frac{c}{b-a}$, where c was the disparity difference between b and a. Disparity was set in the two directions, “crossed” (periphery in front of the screen) and “uncrossed” (periphery behind the screen).

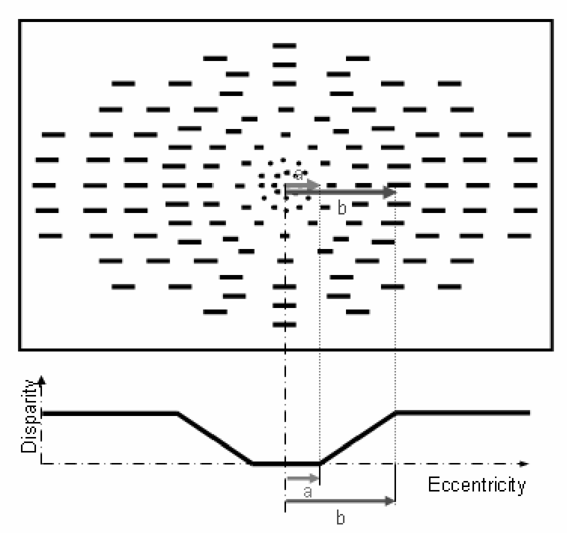

Figure 1: Field of geometric horizontal disparities applied to stimulus (upper). Profile of horizontal disparity variation as a function of eccentricity (lower). *a* is the eccentricity of the beginning of the disparity gradient and *b* is the eccentricity of the end of the disparity gradient.

Observers were seated 65 cm away from the display and used a chin rest in order to stabilize head position throughout the experiment. They were instructed to maintain their fixation to the central point of the stimulus for all the measurement duration, and eye movements were monitored by electro-oculography. The experiment room was carefully darkened so that the observer saw nothing but the stimulus throughout the experiment. The fixation plane was only located by the fixation point.

Pre-fixation images were used between each measurement in order to avoid afterimages of the stimulus on the retina (Figure 2): a white elliptic image, with a black fixation point, presented two seconds, to erase some possible afterimages left on the retina, after the previous measurement, due to the presence of circles on stimulus; and a black image, with a white fixation point, presented four seconds, to re-adapt the retina with a dark environment before each threshold measurement. Note that the white elliptic image was presented after the choice screen, and therefore after the recording of threshold value and perceived depth sign. The presentation durations of the white and the black image were calibrated, on two observers (experienced in psychophysics), to no longer have afterimages of the stimulus on the retina at the beginning of the measurement. We found that with two seconds of white and four seconds of black, no afterimages or no visual masking were reported by the two observers.

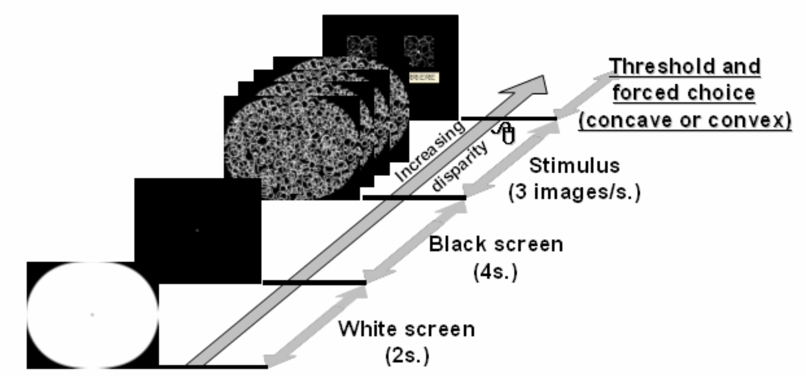

Figure 2: Test sequence. Schematic representation of a threshold measure.

The stimulus consisted of a set of images: each image has a different value of disparity gradient (disparity gradient progressively increased from no disparity gradient for the first image seen, to a disparity gradient for the next images with a fixed increase); and the images of the set were successively presented to the observer (with three images per second). The observer's task was to stop the temporal image succession by a mouse click when he perceived a depth change in the periphery of the stimulus, relative to the perception of the screen plane. An intermediate method between ascending adjustment and ascending limits, where, temporally speaking, the observer triggered the end of disparity gradient increase with a mouse button click, was used to find the point at which the simulated surface appeared to present a depth change in periphery. For one measurement, only the disparity gradient, between two fixed eccentricities, of the stimulus increased. The observer did not really "adjust", but he stopped the disparity gradient increasing when he perceived a depth change. At threshold, the observer had to respond by a mouse click, on the forced choice screen, whether the stimulus periphery was in front of (Figure 3(a)), or behind (Figure 3(b)), the plane of the fixation point? No feedback was given on the correctness of answers. Measurement results with incorrect answers were discarded (the error rate in the choice, relative to the number of repetition for each repeated measurement, was about 1.7%). The observer had a discrimination task, because he was asked to indicate if the deformation he perceived was concave or convex.

Experimental sessions lasted for approximately 30 min, and each observer participated in four sessions. Results from the first experimental session, used for training, were discarded. Detection thresholds were measured for 18 pairs (*a*,*b*) (nine pairs each for crossed and for uncrossed disparity). Sessions consisted of two repeated measurements of the 18 pairs. With three sessions, we collected six repeated measurements for each pair per observer. Therefore, with eight observers, a total of 48 threshold values was collected for each pair.

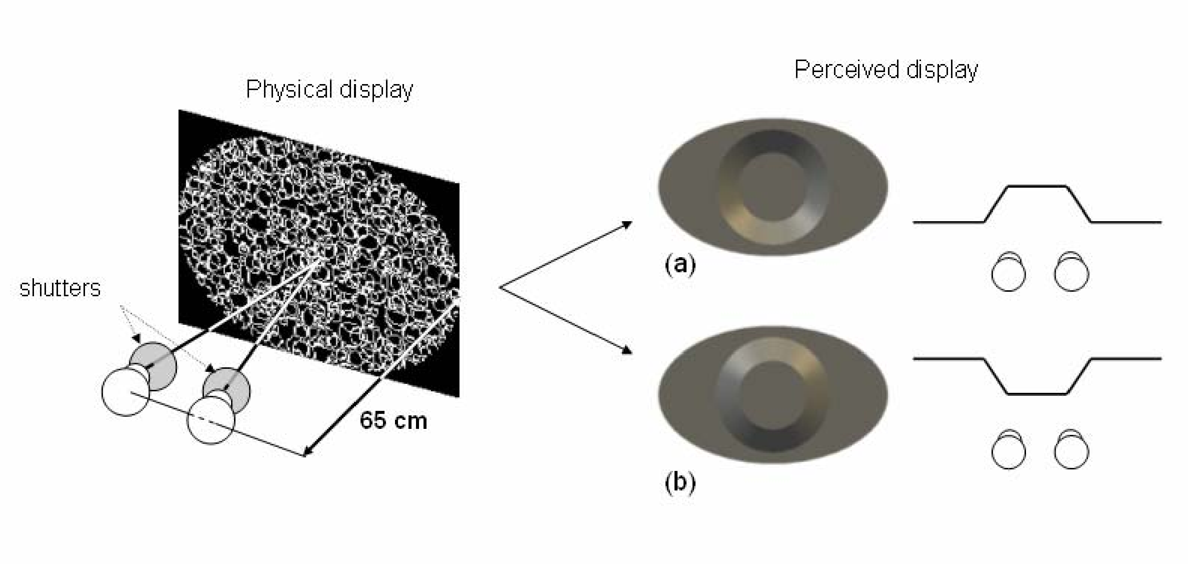

Figure 3: Experimental set-up (left) and observer's predicted depth perception (right): (a) Perceived display with crossed disparities, concave perception. The central disc is normally (in terms of disparity applied) in the screen plane and the peripheral area in front of the screen plane. (b) Perceived display with uncrossed disparities, convex perception. The central disc is also in the screen plane and reciprocally the peripheral area is behind the screen plane.

APPARATUS. To create disparities, we used a dichoptic display allowing to obtain an image for each eye by means of shutters and a stereo display (Figure 3): Stimuli were generated by a Silicon Graphics Zx10 workstation and displayed with a video projector (Electrohome marquee ultra, green monochromatic light, 120 Hz frame rate) on a screen (129 × 96 cm) in front of the observer. Stereograms, 1824 × 1368 pixels, were created using an interlaced frame stereo display synchronized to a pair of electro-optical shutters via an infrared link.

During the stimulus presentation, increment of the image changing was three images per second and increasing of disparity gradient between each image was from 0.94 arcsec/° (central pairs) to 1.30 arcsec/° (peripheral pairs). A set of stereo pairs with the different values of disparity gradient was precomputed for each pair of eccentricities and for each observer, as a function of his interpupillary distance.

At the viewing distance (65 cm), the display subtended 89 × 73° of visual angle (shutters did not limit the visual field), and each pixel (in the 1824 × 1368 display) subtended 224 arcsec at the centre (less than 224 arcsec on periphery).

Eye movements were monitored by an electro-oculographic device (EOG) with a saccade threshold of 6°. When EOG detected a saccade higher than 6°, a buzzer noise was emitted and the current threshold measurement was stopped without recording the disparity value. The detection of saccades by EOG (buzzer noise and repetition of the measurement) was sufficiently unpleasant for the observers to dissuade them from producing eye movement. The discarded first session was made in conditions with EOG and the observers were instructed to maintain the fixation on the fixation point, so they were conscious of the importance of a good fixation all along the duration of the measurements.

STIMULUS. The stimulus was composed of white open circles on a black background with semi-random distribution (Figure 4). Stereogram density was 36%. This stimulus is a cyclopean stereogram with no preferential direction, allowing a continuous depth perception of image. In the terminology used by Van den Enden and Spekreijse (1989), the stimulus has a neutral texture perspective. A Gaussian blurring was applied to avoid detection bias (stimulus flickering at the change of image in the disparity variation location) and to prevent aliasing resulting from the interpolation process. The ring-shape, where the disparity gradient varied, could not be identified monocularly on the stimulus. Monocular cues were ruled out by control trials wherein either left or right eye images were presented to both observers' eyes and two observers attempted force-choice discrimination after adjustment. Under these conditions, the two observers never perceived any depth and always demonstrated chance-level performance, which showed that monocular cues were not present in our stereogram display.

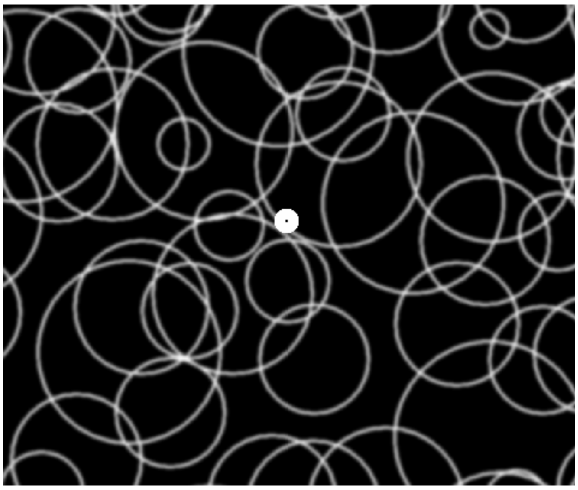

Figure 4: Central part of the stimulus. The fixation point consisted of a white disc in the centre of the image.

The fixation point was a white disc of 1° of visual angle, binocularly seen to aid vergence and fusion, with a small black point in its centre to constrain accommodation on the screen plane (Figure 4). Observers were instructed to maintain the fixation point as a single point and the black point not as a blur point. To avoid seeing the screen edges, stimulus boundaries were elliptic.

OBSERVERS. Eight observers, 3 women and 5 men, aged between 24 and 38, participated in the experiments. All observers had normal visual acuity and good stereo vision (at least 30" stereoacuity by clinical testing).

CONTROL EXPERIMENT. An additional experiment with a method of constant stimuli was carried out as a control: Five values of disparity gradient, always located between 7 and 14° of eccentricity, were chosen for crossed and for uncrossed disparities. These values were presented randomly, briefly (300 ms) and 100 times for each value. Three observers participated and their task was to make a forced choice between “concave” or “convex” perception for each value of disparity gradient. The results were graphically represented by the percentages of “concave” answers for each value of disparity gradient. The data was fitted by a sigmoid curve. The curve equation allowed to have a bias and a discrimination sensitivity. The discrimination thresholds could be approximate by the value corresponding to 75% of good answers.

RESULTS

For each observer, recorded measurements gave several values of disparity gradient for a pair of starting and ending eccentricities and as a function of applied crossed or uncrossed disparities. The stimulus depended on three values: the starting eccentricity (a), the ending eccentricity (b) and the disparity (c). The assumption is that there are two possibilities of detection process: (i) the detection could either be based on the disparity difference (c), or (ii) on the disparity gradient (ratio $\frac{c}{b-a}$). Thresholds of deformation detection, in terms of disparity gradient, were distributed between 18 arcsec/° and 90 arcsec/°. This range of thresholds is explained in the next three parts: (1) variability between observers; (2) difference in thresholds between crossed and uncrossed disparities; (3) some differences in thresholds as a function of pairs (a,b), and therefore as a function of the disparity variation location. Data was analysed using an analysis of variance (ANOVA) with repeated-measures design. The independent variables were: direction of disparity (crossed, uncrossed); starting eccentricity (a: 0, 7, 14°), and angular width of variation (b - a: 7, 14, 21°).

(1) VARIABILITY BETWEEN OBSERVERS. Variability in thresholds between observers is significant for crossed and for uncrossed disparities, as shown by ANOVA ($F_{7,35} = 19.44$, $p < 0.001$ and $F_{7,22} = 55.89$, $p < 0.001$, respectively). The range of results was wide between observers but thresholds of disparity gradient as a function of pairs and for crossed or uncrossed disparities showed similar variations. Note that the repeated measurements did not show a high variation between themselves, because the variability within the observers is not significant for the last five measurements (ANOVA: $F_{4,340} = 2.29$, $p = .06$). Therefore the measurements were steady during the experiment.

On the other hand, a control experiment was carried out with three of the eight observers to test a possible effect of the white screen on the threshold measurements: the absence of the white image did not modify significantly the thresholds (ANOVA: $F_{1,86}$=3.63, p=.06), and there was no interaction between the presence or not of the white image, and the observers (ANOVA: $F_{2,86}$=0.58, p=.56).

To study the variability as a function of pairs, or location parameters of the disparity variation, mean results, in terms of either disparity gradient or disparity difference, at perception threshold of surface deformation for all observers were analysed. For mean results analysis, we compared the effect of the starting eccentricity (a) and of the extent or angular width of the disparity variation (b-a). Each group of variation extent (b - a) was chosen to be equal (7, 14 and 21°). Mean gradient values at threshold for each starting eccentricity value (a) as a function of the extent of disparity variation were represented in Figure 5.

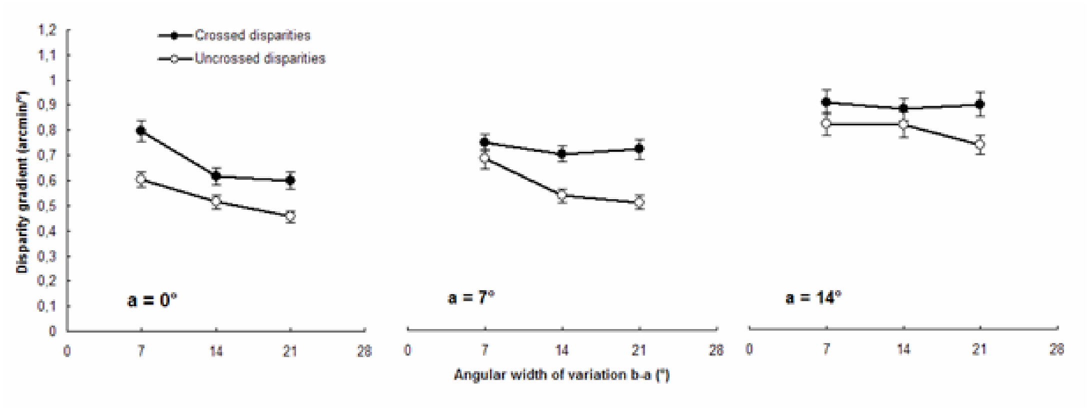

Figure 5: Mean disparity gradient at detection threshold of surface deformation as a function of angular width of disparity variation area (*b-a*) and for the three eccentricities at the beginning of variation (*a*). Closed circles represent crossed disparities and open circles represent uncrossed disparities. Vertical bars indicate ± 1 standard error.

Comparatively to the disparity gradient (i.e. the first spatial derivative of disparity difference), results can be treated as the disparity difference (*c*) between disparities of the ending and starting eccentricities of variation area. Because the disparity of the central disc (whose radius value is *a*) equals zero, disparity difference equal the disparity at the eccentricity point *b*. Figure 6 represents the disparity difference as a function of starting eccentricity (*a*), a graph for each *a* value, and as a function of angular width of disparity variation (*b* - *a*).

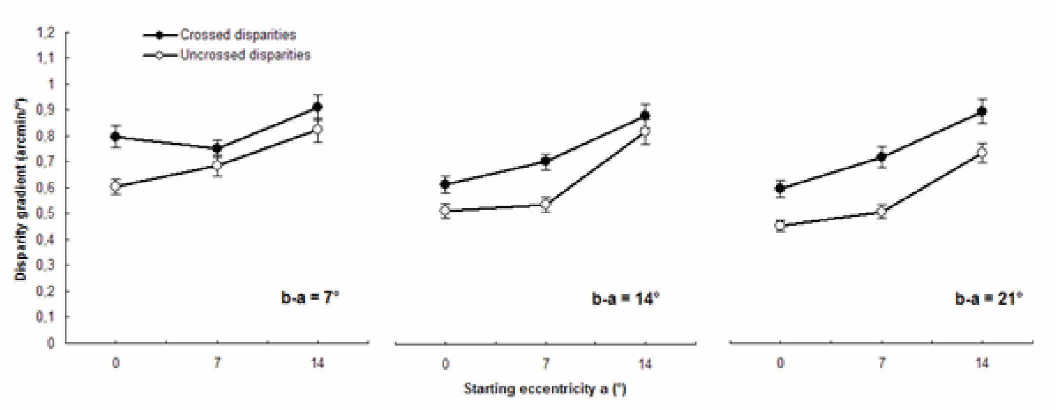

Figure 6: Mean disparity difference between starting and ending eccentricities at detection threshold of surface deformation as a function of angular width of disparity variation area (*b-a*) and for the three eccentricities at the beginning of variation (*a*). Closed circles represent crossed disparities and open circles represent uncrossed disparities. Vertical bars indicate ± 1 standard error.

(2) COMPARISON OF CROSSED AND UNCROSSED DISPARITIES. Firstly, detection thresholds were lower for uncrossed disparities (open circles) than for crossed disparities (closed circles), as can be seen in Figure 5 and Figure 6. An ANOVA confirmed that detection thresholds are significantly different between crossed and uncrossed disparities ($F_{1,57} = 60.76$, $p < .001$). Secondly, there was no significant interaction between crossed and uncrossed disparities (as a function of starting eccentricity (*a*): $F_{2,57} = .045$, $p = .95$), showing that gradients of crossed and uncrossed disparities in deformation detection threshold have the same trend of sensitivity with respect to other experimental conditions. Results therefore showed similar variation relative to the direction of disparity and the most relevant difference between crossed and uncrossed disparities was thresholds which were systematically lower for uncrossed disparities.

(3) INFLUENCE OF DISPARITY GRADIENT LOCATION. Concerning the different parameters of gradient location, the analysis mainly focused on the eccentricity *a* and on the angular width of the variation area (*b* – *a*). At starting eccentricities (*a*) of 7° and 14°, disparity gradient at deformation detection threshold did not vary with angular width of variation area (*b* - *a*) (Figure 5), with the exclusion of pairs (7,14) of uncrossed disparities (7° of angular width). For starting eccentricity above 7°, the thresholds of deformation discrimination did not depend on the spatial extent of disparity variation as shown in Figure 5 and confirmed by ANOVA ($F_{1,26} = 71.89$, $p < .001$). This suggests that the starting eccentricity of 7° is a breakpoint from which the detection would be made on disparity gradient. The Figure 6 corroborates this idea: the thresholds of disparity difference depended heavily on the angular width of variation disparity. Results showed that the thresholds in disparity gradient $\frac{c}{b-a}$ were more constant than the thresholds in disparity difference (*c*). Therefore, results were in favour of a detection of disparity gradient for starting eccentricities beyond 7°.

On the other hand, at a starting eccentricity (*a*) of 0°, disparity gradient at threshold decreased with increasing angular width of variation (Figure 5), and disparity difference at threshold increased with increasing angular width (Figure 6). However, the impact of angular width on disparity gradient sensitivity remains comparatively much weaker than on disparity difference sensitivity (Figure 6). It would seem that detection was not made on disparity gradient nor on disparity difference alone. Moreover, between 0 and 7° of starting eccentricities, disparity gradients are not significantly different for a same angular width “*b* – *a*” (Figure 5) and then, disparity difference between the starting and ending eccentricities is approximately the same for a same angular width (Figure 6). These results did not permit to conclude whether detection was made on disparity gradient or on disparity difference.

Note that Figure 5 and Figure 6 also allow to view the results, respectively in terms of disparity gradient and disparity difference, for stimuli in which the eccentricity *b* (i.e. the end of the disparity variation) remained constant. For a same *b* value (14, 21 or 28°), the disparity gradient increased and the disparity difference decreased, with increasing eccentricity *a*. Therefore, the extent of the disparity “bump” or “trough” (explained below in the Discussion) was not the relevant parameter in the detection of surface deformation.

Therefore, the results showed a dissociation between: on the one hand, the peripheral starts, where the detection was made only on the disparity gradient; and on the other hand, the central starts, where the detection was made neither on the disparity gradient nor on the disparity difference, with precision.

RESULTS OF CONSTANT STIMULI EXPERIMENT. The psychometric functions (sigmoid curves) of the three observers were represented in Figure 7. The value of bias and the discrimination sensitivity (defined by the slope of the curve at 50%) were reported on each graph.

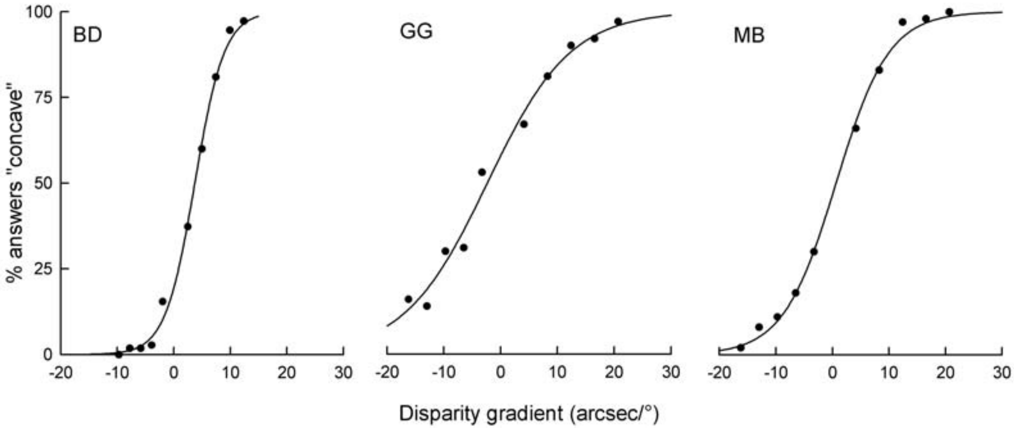

Figure 7: Psychometric curves corresponding to constant stimuli experiment for the three observers. The bias represented the value for 50% of "concave" answers, and the discrimination sensitivity is the slope of the curve at 50% of "concave" answers.

The discrimination thresholds of concave and convex deformation could be approximate by the value corresponding to 75% of good answers (or 25 and 75% of "concave" answers). The mean discrimination threshold of concave deformation, in disparity gradient, was 6 ± 0.5 arcsec/°, which corresponds to threshold of crossed disparity. The mean threshold for uncrossed disparity (convex deformation) was 4.7 ± 5.6 arcsec/°. Observer BD had a bias value (3.72 arcsec/°) in crossed disparity and a sharp slope (9.56), that is to say he had a concave perception of the frontoparallel plane and his convex perception threshold was close to zero arcsec/°.

DISCUSSION

A previous study (Devisme et al., 2004) highlighted that perception thresholds of surface deformation depend not on disparity at a given eccentricity, but on the disparity gradient applied at this eccentricity. Detection of surface deformation would not be based on the value of disparity at a given point but on the disparity gradient at this point. The most relevant gradient factor in this detection would be the eccentricity of the beginning of the disparity variation. Only crossed disparities were studied.

The present study measured deformation detection thresholds for crossed and uncrossed disparities (respectively concave and convex surface deformation) to extend these previous results and to conclude about the processing of horizontal disparity in surface deformation perception, in the peripheral visual field.

DIFFERENCES BETWEEN CROSSED AND UNCROSSED DISPARITIES. The deformation detection thresholds were significantly lower for uncrossed disparities than for crossed disparities. This difference means that the finest detection is for uncrossed disparities, or convex surface deformation. The difference is partly explained by geometrical optics and the fact that the distance scaling of disparity information is different between crossed and uncrossed disparity: the same absolute value of disparity in stereograms gives a larger physical depth for uncrossed disparity than for crossed disparity. Physical depth refers to the position of the stereoscopic form relative to the depth plane of the frontoparallel screen plane in the case of a true depth perception, or, in other words, the distance scaling of disparity information (Cormack & Fox, 1985; Ritter, 1977). Ogle (1958) found that the stereoscopic acuity did not change with increasing distance, whereas, for a same angular disparity value, the physical distance largely increases with an increase in viewing distance. He concluded that the binocular judgement was not based on physical depth. He used a test line at 0.5° of a fixation line, which corresponded to the central area, and the proximity to the fixation point could probably not allow to judge with physical distance. Our experimental conditions were very different in terms of eccentricity to the fixation point and size and shape of the test target. When the disparities lie in a large peripheral field, the visual system could estimate physical depth distance from the frontoparallel plane. Otherwise, the perceived depth seems to correspond to that predicted by the geometry of binocular viewing for crossed disparity and seems to be frequently less than predictions for uncrossed disparity (Patterson & Fox, 1984; Patterson, Moe & Hewitt, 1992). Patterson et al. (1992) investigated physical depth in various conditions (size, duration and distance). Their thresholds were in accordance with physical depth for crossed disparity. For uncrossed direction, they observed an underestimation for a brief duration (160 ms), small size (1° of width) and large distance (150 cm). Our conditions, in terms of duration, size and distance corresponded to the case where there is a good accordance between percept depth and physical depth. In other respects, the method of constant stimuli, used in the complementary experiment, showed a bias in the sense of a convex perception of the frontoparallel plane for two observers (BD and MB), but the third tended to have a bias in the opposite direction, a slight concave perception of the frontoparallel plane. Nevertheless, the calculation of the physical distance perceived stereoscopically relative to a given angular disparity indicates that the difference in physical distance between crossed and uncrossed angular disparities is larger for high disparity value (as obtained with our adjustment method) than for very low disparity value (as with constant stimuli method): for example, a difference of approximately 0.2 arcsec, between crossed and uncrossed disparity of about 36 arcsec, yields an equivalent physical distance for, respectively, in front and rear directions; comparatively, a value of 360 arcsec of crossed disparity creates the same physical distance than a value of 345 arcsec of uncrossed disparity, but in the opposite direction, at 7° of eccentricity. For the angular disparity values measured with the method of constant stimuli (close to 36 arcsec), the physical distances were not so different for crossed and uncrossed direction, and for the ones measured with our adjustment method (more than 360 arcsec), the physical distance is higher for uncrossed than crossed disparities. This physical interpretation could explain why the difference, observed with our adjustment method, is significant in comparison with the constant stimuli method. Therefore the significant difference observed for our adjustment method was not always found with other procedures, depending on the level of disparity values at threshold. If the visual system estimates physical depth distance from the frontoparallel plane, then the same distance in front or behind means larger crossed than uncrossed disparity values, when measured by our adjustment method, that accounts for higher sensitivity for uncrossed disparity, as has been reported.

This better performance for uncrossed disparities can also be explained by the fact that this experiment was carried out in the prehension, or grasping area (65 cm). Indeed, in this near space, there would be a preferential processing of convex surfaces (because humans are used to grasping objects of convex shape) and observers would be more sensitive to objects approaching them (survival concept). In this case, concentric gradients of uncrossed disparity produce convex perceived surfaces, where periphery should be perceived behind fixation plane. Observers reported to perceive the central area approaching, for uncrossed disparity (or moving away for crossed disparity). The observer’s task was to detect a change in depth in peripheral visual field, but observers probably detected more easily a “bump” or a “trough” of various extents in the center of the stimulus. Moreover, the detection of a “bump” moving towards the observer could be faster than a “trough”. The “bump” can also cause faster reaction times and hence could explain the lower thresholds for uncrossed than for crossed disparities. Previous studies found that the detection duration for uncrossed disparity stimuli was longer than for crossed disparity stimuli of the same absolute value (Manning, Finlay, Neill & Frost, 1987; Patterson, Cayko, Short, Flanagan, Moe, Taylor & Day, 1995). Their stimuli were squares between 1 and 4 arc degree at the fixation point or at 3° max of eccentricity, which was the central area regarding the present study. The authors highlighted that the detection was more rapid for the depth in front of, than behind, the fixation plane, as shown by our “bump” (with uncrossed disparities) and “trough” (with crossed disparities), respectively. As Patterson et al. (1995) proposed, discrimination would be made on depth and not on disparity. Becker, Bowd, Shorter, King and Patterson (1999) showed that depth discrimination depended on the depth position of disparity plane relative to background dots at screen distance: when disparate stimuli (crossed and uncrossed) were in front of the background dots, there was no difference between crossed and uncrossed disparities; when disparate stimuli were behind the background dots, difference was low; when uncrossed stimuli were behind and crossed stimuli in front of the background dots, the difference was high. The authors interpreted these discrimination changes by the occlusion of the stimuli by the background dots. In the present experiment, there was no equivalent of the background dots. So that the occlusion effect postulated by Becker et al. could not account in the reported difference between crossed and uncrossed direction. Nevertheless, the background could correspond to the periphery of our stimulus (beyond eccentricity b). In this case, crossed stimuli had the centre behind the periphery (background) and uncrossed stimuli had the centre in front of the periphery (background). Therefore crossed depth discrimination would be in the “back” condition and uncrossed depth discrimination would be in the “front” condition, in the words of Becker et al. (1999), and it could explain why depth discrimination was lower for crossed than for uncrossed disparity.

The observers could already have a convex perception of the screen plane and their frontoparallel reference plane, or their perception of frontoparallel plane, would be slightly concave (crossed disparities). Mainly one observer (BD) out of three really had a bias towards uncrossed disparities with constant stimuli method, which means he would have a convex perception of the frontoparallel plane. For some observers, the bias towards uncrossed disparities could therefore explain the lower thresholds for uncrossed than for crossed disparities. Nevertheless, this control experiment with constant stimuli method did not always reveal the effect of the disparity direction, perhaps because of the small number of observers and because of the physical depth difference between crossed and uncrossed disparity which is less for the low disparity values (see above).

Moreover, previous research on *stereoanomaly* (Richards, 1971) showed differences in sensitivity to crossed and uncrossed disparities, that suggested separate neural processings of crossed and uncrossed stereopsis. For Patterson and Fox (1984), the stereoanomaly highlighted by Richards may rather reflect the method of brief exposure durations used in this case. Our threshold differences between crossed and uncrossed disparities could also be consistent with the different types of disparity-tuned cells found in the monkey and in the cat: *far* cells that are excited by uncrossed disparities and inhibited by crossed, and *near* cells are excited by crossed disparities and inhibited by uncrossed, in striate (V1) and prestriate (V2) cortex of the macaque and in areas 17 and 18 of the cat (Poggio, Motter, Squatrito & Trotter, 1985; Howard, 2002). The existence of the same types of disparity-tuned cells in humans could provide an explanation concerning the difference in sensitivity between crossed and uncrossed disparities.

COMMON BEHAVIOUR FOR BOTH SIGNS OF DISPARITY. Our results highlighted that thresholds of crossed and uncrossed disparities have the same variation as a function of starting eccentricity and as a function of variation extent. In the following, we considered crossed and uncrossed disparities together.

The first observation is the comparison of our thresholds with the ones of previous studies. The specific experimental method made comparison with other literature difficult. On the one hand, in terms of disparity gradient, Mitchison and McKee (1990) reported slant thresholds using surface of a small angular extent (from 0.5 to 2°) for ten observers. Their thresholds for either horizontal or vertical gradient of horizontal disparity were distributed from 1.8 to 426 arcsec/°. Comparatively, our thresholds for concentric disparity gradient and for a large extent were close to the mean value (from 18 to 90 arcsec/°). Our radial gradient of horizontal disparity, which contains gradients in all the orientations, was a combination of vertical gradient and horizontal gradient. Mitchison and McKee (1990) found an anisotropy between horizontal and vertical gradients: vertical gradients were more easily detected than horizontal. In our case, the applied gradient had no preferred orientation, so the thresholds were in the mean value. Our thresholds were measured by a method of adjustment, which is known to produce higher thresholds than a forced choice method. The additional experiment was carried out with a constant stimuli method (control experiment). The mean thresholds, in disparity gradient, were, for crossed disparity 6 ± 0.5 arcsec/°, and for uncrossed disparity 4.7 ± 5.6 arcsec/°. Comparatively, the method of adjustment gave, for the pair (7,14), a mean value of 45 arcsec/° for crossed disparity, and 40.8 arcsec/° for uncrossed disparity. The very low values obtained with the constant stimuli method were in the limit of angular resolution due to the wide visual field of the display. The threshold differences, between the ones measured by the adjustment method and those obtained by the method of constant stimuli, can be explained by hysteresis phenomenon: An initial perception of frontoparallel plane stimulus was kept, with a progressive disparity increase, for a larger disparity limit than that of a stimulus that was presented briefly alone. Other explanations could be the adaptation usually observed with an adjustment method and a possible level of confidence in the perception of deformation. Nevertheless, observers were relatively constant in their thresholds with this method. Therefore, during the experiment, the observers must have kept the same strategy in their decision to detect the deformation, which permitted us to be confident in the threshold values. Note that the thresholds of 40.8 and 45 arcsec/° of magnitude for respectively uncrossed and crossed disparity, measured by our adjustment method, corresponded to more than 99% of convex or concave answers with method of constant stimuli (see Figure 7). Threshold values with constant stimuli method correspond to 75% of good answers (concave or convex). If the effect was only due to a high level of confidence (if no adaptation occured), the thresholds we observed in adjustment method would indicate that the observers waited until reaching 99% of confidence. This seems clearly implausible, taking into account the instructions given to the observers, to respond as quickly as possible. Therefore, this high percentage of good answers, for threshold values with our adjustment method, suggests that the adaptation effect plays an important role. Finally, the experimental conditions of our adjustment method are closer to a natural condition than of a constant stimuli method: disparities rarely appear suddenly in the visual field as presented in constant stimuli method, and observers are not constrained. A good example of frequent situations in which disparities are maintained in the visual field is ophthalmic glasses with which the deformations created are permanent. The lenses produce disparity gradients in the visual field and the report of wearers is the tolerance for deformation, induced by the disparity field.

On the other hand, some authors studied the sensitivity to disparity corrugations. In terms of disparity corrugation, our stimulus, with disparity gradient between two eccentricities, represented a ramp, and then it contained a wide range of corrugation frequencies. Prince and Rogers (1998) used a circumferential disparity modulation in an annular area with a constant width. Our thresholds were higher than theirs. Comparison with Prince and Rogers' study can only be made for 0, 7 and 13° of eccentricity (14° for our study). The peak of frequency in our disparity modulation was the fundamental frequency (1/40° = 0,025 cpd), and then it was lower than spatial frequencies studied by Prince and Rogers. In these conditions, they reported disparity threshold approximately three times lower (~ 18 arcsec) than in the present study (> 300 arcsec) for 13° of eccentricity, and more for the other eccentricities. Detection of disparity corrugations could be made at the borders of the annulus, this could be easier in their study than in ours, in terms of depth contrast. Bradshaw and Rogers (1999) reported disparity sensitivity functions for horizontal or vertical corrugations in the central area (corresponding to our 0° of eccentricity). They obtained a mean threshold of horizontally oriented corrugations for 0.025 cpd approximately eight times less (~ 30 arcsec) than our mean threshold at 0° (> 250 arcsec), vertically oriented corrugations were not tested for this low spatial frequency. In our study, central presentation was neither purely horizontal nor purely vertical corrugation but a cone expanding in all directions. 30 arcsec of horizontal corrugations for 0.025 cpd corresponds to a disparity gradient of 1.5 arcsec/°, in our experiment. The limitation of angular resolution, because of the large visual extent, could explain these differences in thresholds, essentially for the central area. With decreasing spatial disparity to low spatial frequencies, thresholds of the two experiments, cited above, increased. Our results corresponding to extremely low spatial frequencies are consistent with this effect.

The second observation is that two areas of disparity variation can be distinguished in the visual field:

- Peripheral area: Figure 5 (centre and right graphs) shows that detection in periphery was mainly based on disparity gradient and not on disparity difference (Figure 6, centre and right graphs).
- Central area: Left graph of Figure 5 indicates that detection in central area seems to be based on a combination between disparity gradient and disparity difference (left graph of Figure 6).

The difference between these two areas can be firstly explained by the fact that deformations were conical for central pairs and truncated cones for peripheral pairs. Shape from disparity was not the same depending on the two cases and therefore disparity processing could be different.

Secondly, the difference between central and peripheral area can be explained by the stimulus surface on which the disparity gradient was applied, relative to the whole surface of the stimulus (2% for the smallest central cone and 9% for a conical deformation of 14° of radius, versus 31%, for example, for a truncated cone of 14° of angular width in periphery).

Thirdly, if the assumption is that the detection is made on discontinuity of disparity gradient (Mitchison & Westheimer, 1984), the central case was special because the discontinuity was only a point, compared to the other cases where it was a circle. And in terms of detection of gradient discontinuity, it would be easier to perceive a circle than a single point.

Rawlings and Shipley (1969) measured thresholds of stereoscopic discrimination for horizontal disparities as a function of eccentricity, up to an eccentricity of 8°. Their stereoacuity thresholds ranged from 216 arcsec at 6° of eccentricity to 360 arcsec at an eccentricity of 8°, this approximately corresponds to the value we found in disparity difference for the pair (0,7), this is also, in this case, the disparity at the eccentricity of 7°.

Therefore, for disparity variation in the central area, the visual system could detect a depth contrast between the peripheral area (with continuous disparity) and the central point that represents a disc of 1° diameter (see Figure 4). We could relate this phenomenon of depth contrast to the notion of *salience* (Mitchison & Westheimer, 1984; Westheimer, 1986; Westheimer & Levi, 1987). Detection would thus be made part on disparity gradient and part on a depth contrast for disparity variation in the central area, whereas it would be made mainly on disparity gradient in the peripheral area.

REFERENCE PLANE. As reported by observers, the central area of the stimulus was perceived to approach for uncrossed disparity (or move away for crossed disparity). Therefore, deformation was probably judged by the observers by taking "periphery as a reference" and the observers perceived the central area as detached from their "reference plane". Some previous studies showed that the sensitivity of the human stereoscopic system is determined by disparity of points compared to a local reference plane (Glennerster et al., 2002; Petrov & Glennerster, 2004; Glennerster & McKee, 2004). While, in our experiment, observers were instructed to hold fixation on the central point, the reference plane associated to their perceptive judgment was rather defined by the peripheral stimulus.

The fact that the fixation point with null disparity was perceived to change in depth could also be explained with the effect of residual cues, such as accommodation, which was normally fixed on the fixation point. Inappropriate screen cue (inappropriate focus screen) can have a significant effect on 3D percepts (Watt, Banks, Ernst & Zumer, 2002; Watt, Akeley & Banks, 2003).

Another reason why the reference plane was not the screen plane could be the fact that the screen plane is only represented by a disc of 1°, whereas the peripheral plane occupies a much larger area of visual field.

CONCLUSION

The present study provided quantitative estimates of the sensitivity of human observers in a task of surface deformation discrimination, in the cases of concave or convex deformations, obtained with gradient of horizontal disparities (respectively crossed or uncrossed).

The detection of convex deformations is finer than the detection of concave deformations. This is ecologically explained by the fact that we have always been used to grasping convex surfaces and we are more sensitive to objects which move towards us (it is the case of convex deformations for which we perceive the central part approaching us). Moreover, the deformation was judged by the observer by taking “periphery as a reference”. Indeed, observers perceived the central area which is detached from their “reference plane”. For uncrossed and crossed disparities, the periphery should be perceived respectively behind and in front of the screen plane. However some observers reported perceiving the central area respectively in front of and behind its true position, or in other words the central area seems to move towards or away from the observers. Therefore, the fixation plane was not the observers' reference plane for peripheral judgment.

For disparity variations located in the peripheral area, the detection thresholds depend on disparity gradient and on the starting eccentricity of disparity variation, whereas for those started in the central area, the detection is based neither precisely on disparity gradient nor on disparity difference. In the central area, the visual system could detect depth contrast more than disparity: it could process the discontinuities of constant disparity varitations. In the peripheral area, the processing of horizontal disparity would be more global.

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