

## Spatial size limits in stereoscopic vision

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**Abstract**—Stereoscopic vision is extremely precise in detecting minute differences between adjacent depth planes, but quite imprecise in estimating absolute depth. In this paper, we address the issue of the *spatial acuity* (and not the stereo acuity) of stereopsis. Static RDS (random dot stereograms) stimuli were used to find the spatial grain in which human stereoscopic vision operates. Using psychophysical experiments it was found that foveally, stimuli smaller than 8' cannot be accurately perceived. For other eccentricities, it was found that this threshold is inversely proportional to the Cortical Magnification factor. We interpret this spatial size limit, which is an order of magnitude larger than visual spatial acuity, as an indication that stereopsis is an area based comparison rather than a point process, and discuss the relations between the cortical 'patch' size that corresponds to this 8' limit and Ocular Dominance Columns.

### INTRODUCTION

Much work has been done to discover various functional parameters of stereoscopic vision. A parameter which is frequently examined is *stereoacuity* (stereo depth acuity), determined by the disparity threshold (smallest detectable disparity that yields correct depth perception). Ogle (Ogle, 1950; Ogle, 1952) examined Panum's fusional area, that can be expressed as a range of disparities in which a stereoscopically presented object appears fused and single. Another variable that has been examined is the *contrast sensitivity* (Frisby and Mayhew, 1978; Arditi, 1986; Halpern and Blake, 1988).

The common emphasis, in measurement of stereoacuity, is on the depth (disparity) domain. Disparities of only a few seconds of arc are detectable (Westheimer, 1994) classifying stereoscopic vision as a *hyperacuity*. On the other hand, humans' ability to estimate absolute depth is quite poor. McKee *et al.* (1990) describe psychophysical experiments showing that although the minimum detectable disparity is indeed as small as a few seconds of arc, the disparity increment thresholds are considerably higher than those of visual (spatial) acuity. They termed this the *imprecision* of stereopsis.

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The *spatial* acuity of stereoscopic vision is seldom examined. Indirect relation to the issue of spatial acuity could be found, for example, in Burt and Julesz (1980) and Westheimer (1986). Burt and Julesz (1980) have examined displays with more than one object and found a limit on the disparity gradient, defined as the difference in the disparity of two objects, divided by their separation in visual angle. Westheimer (1986) described an interaction between the depth of adjacent stimuli. He noticed that when two stimuli are only a few minutes of arc apart, a sort of pooling occurs between their two disparities, and the stimuli seem attracted to each other (in depth). On larger distances between the objects (more than 6') the objects act as if they repelled each other in depth.

It is well known that Spatial frequency effects the disparity thresholds (Schor *et al.*, 1984; Wilson *et al.*, 1988; Kontsevich and Tyler, 1994). Legge and Gu (1989) used gratings to examine the effect of spatial frequency on the minimal disparity threshold. They discovered that thresholds were lowest near a spatial frequency of 3 cycles/deg, and rose in proportion to spatial period at lower frequencies. Above 3 cycles/deg the pattern of results changed to higher threshold values or to a plateau.

Tyler (1973) performed an experiment from which the spatial acuity of stereopsis can be estimated quite directly. His study revealed a limit on the ability of stereoscopic vision to perceive depth in stimuli with details of a grain finer than 3 cycles/deg. While presenting subjects with vertical line stimuli containing sinusoidal disparity variations, Tyler noticed that a sinusoidal of frequency higher than this value was clearly visible monocularly, however a stereoscopic image with the same curvature did not elicit depth perception. Thus, within a region of 10' (the distance between a minimum and a maximum of a sinusoidal grating) depth differences were not apparent.

Other works (Tyler, 1974; Tyler and Julesz, 1980) which investigate the high spatial frequency limitation of stereopsis describe a limit of 3–5 cycles/deg on the spatial frequencies. In the words of Tyler and Julesz (1980), 'This is equivalent to saying that the depth image is quite blurred compared to the monocular acuities which can extend beyond 50 cycles/deg'.

All these studies that imply that stereoscopic vision operates in a manner much coarser than monocular (i.e. non-stereoscopic) vision, were a major motivation to the present work. Our goal was to examine explicitly the spatial resolution (grain) for binocularly fused images.

Static RDS (random dot stereograms) (Julesz, 1960) were used in order to avoid any monocularly visible depth cue. As in the classical experiments, we have used only horizontal disparities. Our experiments meant to find what is the smallest object embedded in RDS that could be accurately perceived. In the first experiment, stimuli were presented foveally. In the second experiment, stimuli were presented at various eccentricities in order to examine the influence of eccentricity on the obtained threshold.

Previous works which investigated the influence of spatial frequency on stereopsis, usually used gratings or other kinds of stimuli which pose a limit on one axis alone (usually horizontal gratings). Under such experimental circumstances, one can not rule out the possibility that some global interactions take place. It is possible, for example, that while any local process does not supply an accurate estimate of disparity,

a cooperative process that takes into account multiple local measurements can in fact achieve higher accuracy than the local ones. A typical example of this phenomenon is the classical aperture problem. In the experiments described in the present paper, a small square was embedded in a RDS, enabling us to avoid global interaction that possibly occurred in previous works, and examine the sheer local properties of stereopsis. Although there exists similarity between the stimuli used here and in previous works, the question handled by the current study, has not been examined directly before.

### GENERAL METHODS

Static random dot stereograms were used, consisting of 15% white dots, over a black background. Images were generated and displayed on a Silicon Graphics computer with a CRT monitor with resolution  $1280 \times 1024$ . When displaying stereo images the actual resolution is only  $1280 \times 512$  for each eye, with pixels of doubled height. The images of both eyes were displayed alternatively on the CRT, and viewed using LCD shutter glasses synchronized with the displayed image, which blocked each eye alternatively, while the image of the other eye was being displayed. The background luminance was  $4 \times 10^{-3}$  cd/m<sup>2</sup>, and the luminance of the white area was 3 cd/m<sup>2</sup>. The images were viewed at a distance of 54 cm from the CRT, in which the angular width of each screen pixel was 1.5'.

Four subjects participated in the experiments, all with normal stereoscopic vision, and normal or corrected to normal visual acuity. Prior to the experiments, each subject has been given sufficient training, until his results appeared stable.

All the experiments were two-alternatives, forced choice. After the images were displayed, the subject had to press one of two keys to specify his choice. A blank screen was displayed between successive RDS displays. Stimuli were displayed for presentation durations of 2 s, half a second, and a shorter display time of 150 ms, yielding similar results. Stimuli were presented foveally in the first experiment, and at eccentricities of 10 and 20 deg in the second experiment. Stimuli were presented with various values of disparity in the range 3' to 9' which is within the range of Panum's area, thus should yield a single and fused perception of depth.

In order to confirm that the spatial frequencies of the 2D RDS pattern (not to be confused with the disparity spatial frequency!) of the stimuli do not influence the results, the dots' size was varied by repeating the experiments at various distances from the screen (40 cm and 108 cm), yielding thresholds of similar values (in minutes of arc). The experiments were carried out also for RDS densities other than 15% (up to 50%), resulting in similar threshold values.

## EXPERIMENT 1: MINIMAL SQUARE SIZE THRESHOLD IN THE FOVEA

### Methods

A subject was presented foveally with random dot stereograms that embed the image of a square. The size of the square was varied in order to find the size threshold — the minimal size of the square that yields depth perception (see Fig. 1).

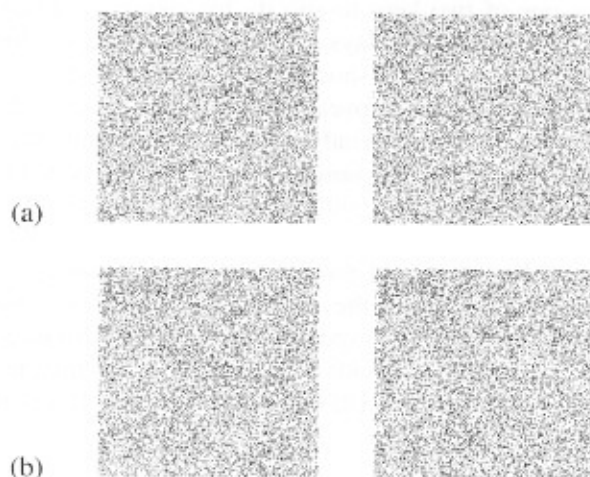
Disparity was either crossed (the square emerging in front of the horopter) or uncrossed (behind the horopter), and the subject had to indicate, by pressing one of two keys, whether he perceives the object as being in front or behind the background. The width of the square was varied from 6' to 24' in steps of 3', each stimulus repeated (with a different random dot array) 20 times, with crossed and uncrossed disparities distributed equally. The series of stimuli was presented at a random order, with a delay of 4 s between successive images.

The experiment was repeated for two subjects using four different values of disparity, all within the range of Panum's area, in order to examine the effect of disparity on this threshold.

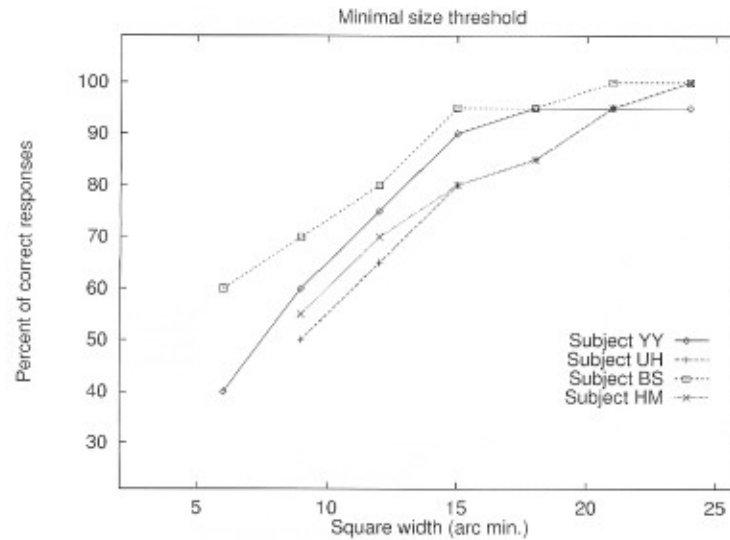
### Results

Figure 2 presents the results of the first experiment at a disparity of 6'. The threshold at which the percent of correct responses is 75% is at 10'–15'.

This experiment was also repeated at various distances from the screen (in order to vary the spatial frequencies of the stimuli), and using several percentages of dots in the random dot stereograms. The resulting thresholds were again within the range 10'–15'.



**Figure 1.** Stimuli used in the experiment: a square is embedded in a RDS. When viewed from 30 cm, the width of the square is: (a) 7'; (b) 20'. Note that the printed image is inverted (in order to efficiently use the printer resolution): it contains 15% black dots over a white background, whereas the stimuli used in the experiments consisting of 15% white dots, over a black background.



**Figure 2.** Results of Experiment 1: percent of correct responses as a function of the width of the square (disparity =  $6'$ ).

Repeating the experiment using different values of disparity, resulted in the curves presented in Fig. 3. These results manifest lower thresholds for smaller disparities for both of the subjects.

This threshold implies that stereoscopic vision cannot detect and perceive correctly objects smaller than  $8'$ – $15'$  (depending on the disparity). Note that this threshold is well above the visual acuity threshold which is about  $0.5'$ – $1'$  (Olzak and Thomas, 1986). This means that although RDS based stereopsis provides extremely accurate estimates of depth (in the  $Z$  axis), in the spatial ( $X$ – $Y$  axis) domain, its accuracy is relatively poor.

#### EXPERIMENT 2: MINIMAL SQUARE SIZE THRESHOLD AT VARIOUS ECCENTRICITIES

The performance of the human visual system, as measured in many visual tasks, largely depends on the retinal eccentricity at which stimuli are being shown. In many cases these differences in performance are explained as a consequence of the non-uniform scale of the retino-cortical mapping, while assuming that in the cortical level these tasks are all performed in a uniform manner (cortical homogeneity). The *cortical magnification factor* ( $M$ ) is defined as the distance in mm along the cortex, concerned with one degree of the visual field (Daniel and Whitteridge, 1959; Daniel and Whitteridge, 1961). Accordingly, *M-scaling* (Virsu and Rovamo, 1979) can be used to scale various stimuli such that the cortical representation of the stimuli remains the same at different eccentricities.

The objective of the second experiment was to test whether the spatial acuity of stereopsis can be  $M$ -scaled.

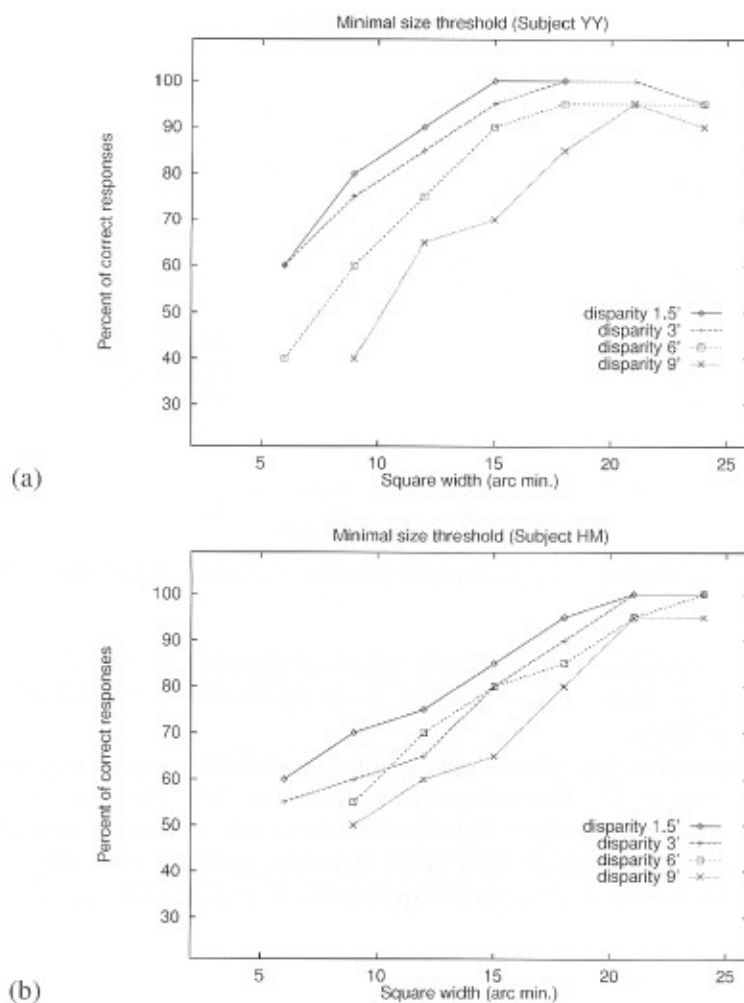


Figure 3. Results of Experiment 1 for various values of disparity: (a) subject *YY*; (b) subject *HM*.

### Methods

The second experiment was similar to the first one, but this time stimuli were presented at eccentricities of 10 and 20 deg. The range of square sizes that was used and the value of disparity at which the objects were presented were calculated using the estimates of  $M$  provided by Rovamo and Virsu (1979) (see below). A preliminary experiment verified that these are the appropriate ranges required for detecting the thresholds. The following ranges of widths were used:

- At the central fovea, stimuli widths were varied in the range 6'–24', in steps of 3'.
- At eccentricity of 10 deg, stimuli widths were varied in the range 20'–90', in steps of 10'.

- At eccentricity of 20 deg, stimuli widths were varied in the range 40'–180', in steps of 20'.

As before, a subject was presented with random dot stereograms that embed the image of a square with either crossed or uncrossed disparity and he had to indicate, whether he perceives the object as being in front or behind the background.

Each stimulus was repeated (with a different random dot array) 40 times by one of the subjects (*BS*) and 20 times by the other subject (*YY*), with crossed and uncrossed disparities distributed equally. The series of stimuli was presented at a random order, with a delay of 4 s between successive images.

Two of the four subjects who participated in the first experiment took part in this experiment. Again, subjects were presented with RDS displays, but this time they were asked to fixate on a white cross that was displayed on the screen throughout the experiment. While they were fixating at the cross, a stimulus was presented at the given eccentricity (10 or 20 deg), and they were asked to make their choice while maintaining their fixation point.

### Results

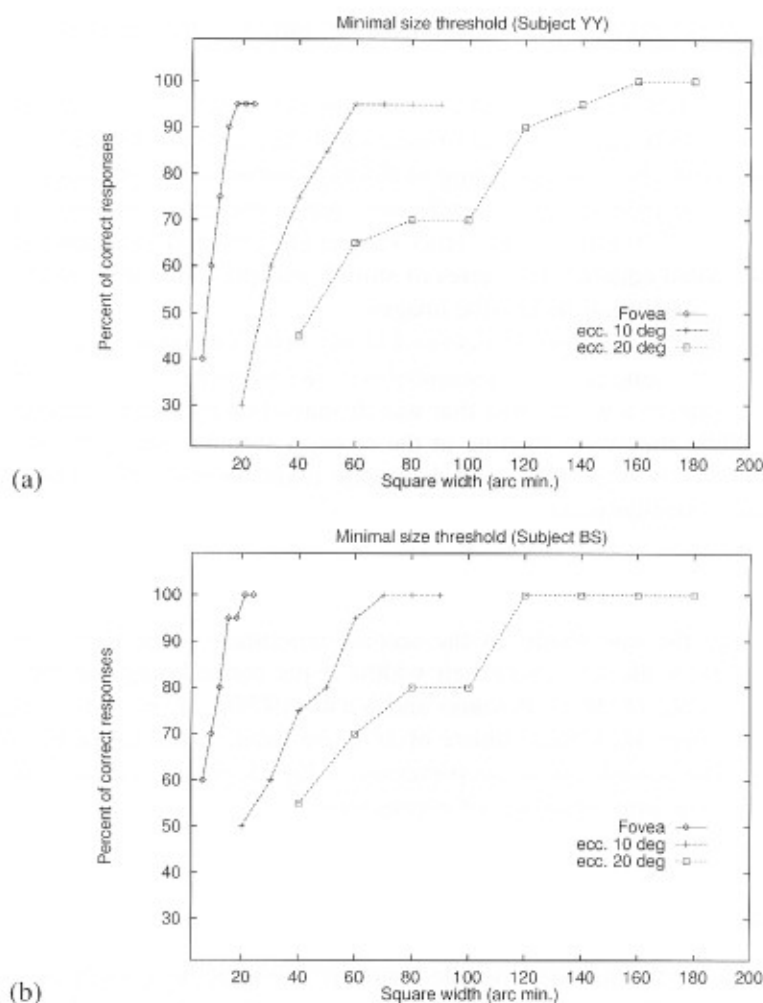
Figure 4 presents the raw results of the second experiment. The next step was to convert the widths of the squares to their widths in the cortical mapping, by dividing them by the estimate of  $M$  of Rovamo and Virsu (1979):  $M = M_0(1 + 0.33E + 0.00007E^3)^{-1}$ , where  $M_0$  is the estimate of  $M$  in the most central fovea, estimated at 7.99 mm/deg. The scaled results are presented in Fig. 5. These scaled curves show a similar acuity function, regardless of eccentricity.

### DISCUSSION

Our experiments imply that stereoscopic vision is operating at a much coarser grid than visual acuity. Stereopsis exhibited an acuity of 8' in the spatial domain for binocularly fused images, compared to visual acuity of about 0.5'–1' (Olzak and Thomas, 1986), and to the diameter of a foveal retinal photoreceptor which is about 0.5' (Westheimer, 1994).

Our findings show that the object's size is an important parameter of stereoscopic vision. Stereoscopic vision is extremely accurate in finding the depth of an object, but its acuity in space is quite poor, as manifested by a spatial threshold that is considerably larger than the disparity threshold for stereopsis (8' rather than a few seconds of arc). Repeating the stimulus size experiment at different eccentricities, yields thresholds that scale in inverse proportion to the cortical magnification factor.

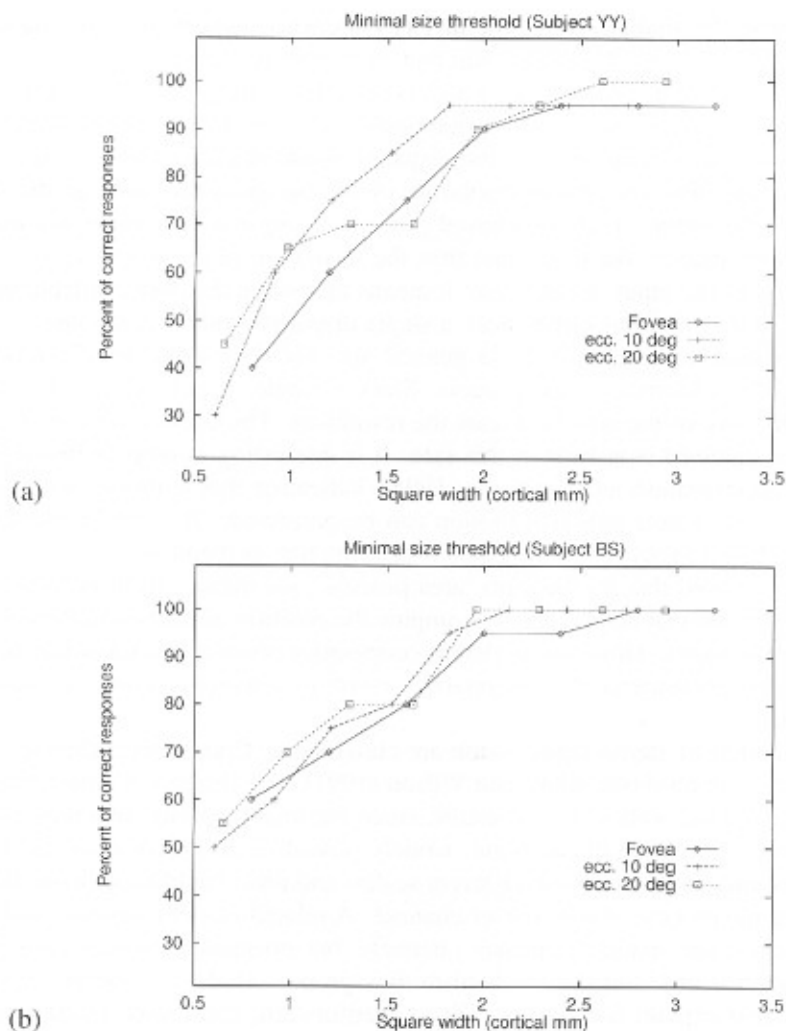
These limitations of stereopsis do not pose a problem in the processing of natural scenes, since the presence of monocular cues and multiple spatial scale (Wilson *et al.*, 1991) allows the use of other visual mechanisms to determine the object's 3D shape, based on depth estimation. The use of RDS stimuli can further manifest the coarser grain of stereopsis, since the shape is not visible monocularly.



**Figure 4.** Results of Experiment 2: the results at eccentricities of 0, 10, 20 deg: (a) subject *YY*; (b) subject *BS*.

The results reported here are obviously limited to artificial stimuli bearing no monocular cues, such as RDS, since humans can readily perceive objects smaller than  $8'$  in natural images. We suggest, however, that our findings point at some fundamental mechanism that takes place in the process of stereopsis. The most important observation that can be derived from stereo fusion of RDS is that the visual system indeed employs a 'context free' correspondence mechanism, that directly tries to match the left and right images. We stress that this mechanism is operating in a very coarse manner, and produces a low resolution depth map. This map, however, could be greatly refined once other visual information flows in. For example, taking into account information of multiple scales, the exact location of edges, or colour and texture borders, could be used to carry out more accurate spatial location.





**Figure 5.** Results of Experiment 2: the results obtained at various eccentricities were converted to mm of cortex using the cortical magnification factor (see text): percent of correct responses as a function of the cortical width of the square (in mm). Data is presented at eccentricities: 0, 10, 20 deg: (a) subject YY; (b) subject BS.

Thus, our results could be interpreted also as an indication that the visual system is calculating, initially, the first coarse approximation of the depth map (and maybe other maps (Hermush and Yeshurun, 1995)), and refines this map as other cues flow in.

Our results are in agreement with the previous results of Tyler (1973). This finding, that depth could not be accurately perceived in stimuli with details of a grain finer than 3 cycles/deg, could be interpreted to predict that the spatial acuity of stereopsis is about  $10'$  (the distance between a minimum and a maximum of a sinusoidal grating). This value is comparable with the acuity threshold of  $8'$  that we found. Our results

agree also with the finding of Westheimer (1994), who suggests that 'the mosaic of disparity detection is much coarser than that of feature detection'.

The spatial size limit in stereopsis, which is an order of magnitude larger than visual spatial acuity, seems to indicate that stereopsis is an area based process rather than a point process. In a point process, the disparity is estimated for every 'pixel' in the input image, and thus the spatial resolution of the output is the same as the spatial resolution of the input. In an area based process, a single output value is computed only for whole areas of the input, and thus the resolution of the output is lower than the resolution of the input. In our case, it means that when the only available input is pure disparity (i.e. no monocular cues), a single disparity value is computed for every 'area' rather than for every 'pixel'. In general, the size constant of an area process is revealed by the resolution of the process. Since a single output value is assigned to each area, the size of the area is at least the resolution. Thus, a size limit of  $8'$  means that the area involved is at least of this size. It is interesting to note, in this regard, a recent finding (Hermush and Yeshurun, 1995), indicating that within a visual area of about  $10'$ , only a single coherent motion can be perceived. This might suggest that similar area based processing take place also in motion perception.

It should be noted that by the term 'area process', we mean a local process. Thus, every local process can not accurately compute the position of the border between two adjacent depth planes. However, a global, cooperative process that takes into account multiple coarse measurements, can possibly result in a more accurate calculation of the position.

Current models of stereoscopic vision are classified as Cooperative, Coarse-to-fine, and Direct feedforward (see Blake and Wilson (1991) for a review). Cooperative models do not agree too well with our results, since the final disparity map they estimate is in the same resolution of the input, namely, visual acuity. Coarse-to-fine models carry out the matching process in different scales, and thus, could explain our findings as reflecting the process of the coarser channel. A related model (Schumer and Ganz, 1979) does not use spatial frequency channels, but postulates the existence of two different mechanisms, and the mechanism they propose to detect 'abrupt changes in depth' can also explain our results. Direct feedforward, area based models such as Yeshurun and Schwartz (1989) and Ludwig *et al.* (1994), indeed predict that a *single* depth (disparity) estimate would be associated with each 'area patch'. The size limit of  $8'$  would suggest that the size of each patch should be larger than  $8'$ . Cormack *et al.* (1991) also proposed a model for stereopsis based on direct cross-correlation of small patches of the visual scene. This model will fit our current results, assuming patches of a size that is larger than  $8'$ .

What could be the neural basis for the limit that we have found? We are looking for a natural tessellation of the visual cortex, where each 'patch' spans about  $8'$ . A fundamental cortical structure that has a size constant about an order of magnitude larger than visual acuity is the visual hypercolumn. Thus, a simple model that will predict the results we have obtained is based on a direct comparison of image patches from the left eye with the corresponding image patches from the right eye. This spatial organization is indeed realized by the Ocular Dominance Columnar (ODC) system (Yeshurun and Schwartz, 1989). In order to find out how plausible is this

assumption, we shall now review available data related to the visual angular extent represented by a single ODC.

The disposition in the visual field between two neighbouring hypercolumns for humans can be calculated using estimates of the *cortical magnification factor* ( $M$ ). Many estimates of  $M$  in the central fovea have been given: 8 mm/deg (Rovamo and Virsu, 1979), 11.5 mm/deg (Drasdo, 1977), 15 mm/deg (Cowey and Rolls, 1974), 20–25 mm/deg (Tolhurst and Ling, 1988).

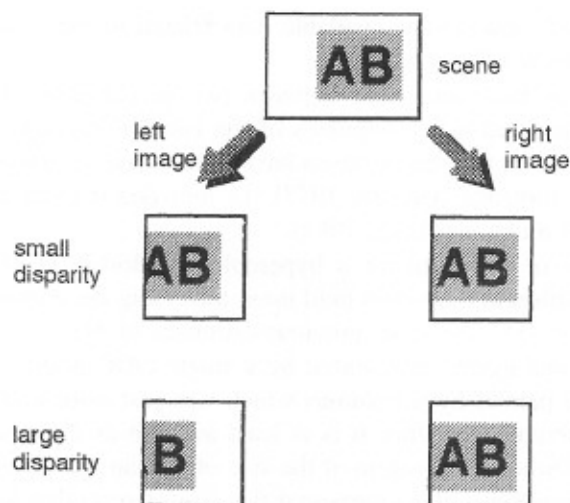
Assuming a size of 1–2 mm for a hypercolumn (Horton *et al.*, 1990), we can estimate the disposition in the visual field upon traversing the cortical map along one hypercolumn as 2.4'–15', using the previous estimates of  $M$ .

However, the visual extent represented by a single ODC is different than the disposition between a pair of hypercolumns which was just estimated and it should be estimated in a different way, since it is at least as large as the size of the receptive fields of its cells. Direct examination of the size of human receptive fields is unavailable. Parker and Hawken (1988) measured the size of receptive fields in the foveal striate cortex (V1) in old world monkeys. They obtained measurements in the range 5'–20' for 63% of the simple cells and 61% of the complex cells. The median was 15' for simple cells, and 13' for complex cells.

Oehler (1985) cross examined the size of the human and Rhesus monkey receptive and perceptive fields. He found an excellent agreement between the behaviourally determined perceptive field centre size, and the receptive field centre sizes of broadband retinal ganglion cells. An examination of the human perceptive fields yielded results similar to that of the monkeys. Therefore it may be concluded that the size of human receptive fields is around the same values described above for the monkeys. The receptive field size is at least the angular disposition along a hypercolumn (shown to be 2.4'–15'), meaning that a hypercolumn receives information from a visual field which is larger than the disposition between two neighbouring hypercolumns. Thus a notion of *overlapping* ODC emerges. Taking into consideration the calculation based on  $M$ , as well as typical sizes of receptive fields and the large variations in the different estimates, it seems plausible that a visual angular extent of 8'–12' is represented within each ODC. Thus, it is indeed plausible that the coarse grid reflected by our results is related to the fundamental hypercolumnar grid.

The results obtained for different values of disparity demonstrate that the spatial acuity threshold decreases with decreasing disparity. This is exactly what one would expect from a mechanism that utilizes area correlation on fixed size patches where the visual scene is projected to left and right patches: small disparity yields much overlap between the representation of the visual scene on the two (left/right) patches. As disparity grows larger, smaller parts of the scene are represented on adjacent patches (see Fig. 6).

A computer simulation of the model was used to examine this prediction. The algorithm of Yeshurun and Schwartz (1989) as implemented in *MATLAB* and run on a Silicon Graphics computer. The input to the algorithm was a pair of area patches of the size 20 × 20 pixels, extracted from stimuli similar to those presented to the human subjects in the psychophysical experiments (RDS that embed the image of



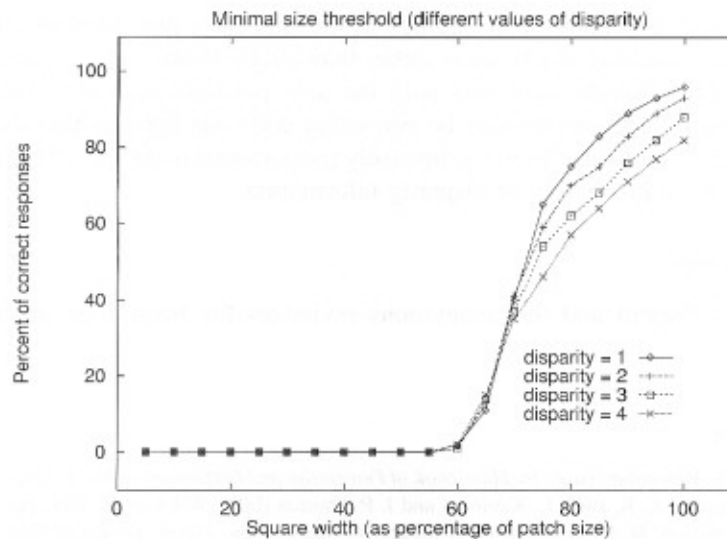
**Figure 6.** An illustration of the effect of disparity on the amount of overlap between the two area patches.

a square). The maximum of the cross-correlation operator was used to calculate a single disparity value.

The width of the square embedded in the RDS was varied in the range 1 to 20 pixels and the disparity was varied in the range 1 to 4 pixels. The simulation was applied to a large series of RDS's, in which each set of parameters (size and disparity) was repeated in 500 different RDS's. According to the estimates derived above, of a visual angular extent of an ODC ( $8'$ – $12'$ ) and the disposition between neighbouring hypercolumns which was estimated at  $2.4'$ – $15'$ , there exists a certain amount of overlapping between neighbouring ODC. We have assumed an overlapping of 50% in the simulation. Thus, the left side of the square embedded in the RDS was positioned uniformly in the left half of the area patch, since the right half is shared with the neighbouring area patch.

For each RDS, the disparity value calculated by the algorithm was compared to the disparity that was used in creating the images, counting the number of times in which correct disparity was detected. The percentage of correct responses made by the computer simulation for four values of disparity are presented in Fig. 7. As can be seen, when the width of the square is larger than 75% of the total width of each area patch in the simulation, the percent of correct responses given by the simulation increases beyond 75%. These curves also show that as disparity grows larger the square embedded in the RDS has to be larger in order for its depth to be correctly detected, as was predicted earlier. The same results were described above, for the human subjects.

When comparing the present results with those of previous works that investigated the influence of spatial frequency on stereopsis, it should be noted that unlike the experiments which use gratings or other of stimuli which pose a limit on one axis alone (usually horizontal gratings) (Schumer and Ganz, 1979), the experiments described here use (like Tyler and Julesz (1980)) a small square embedded in an RDS. This



**Figure 7.** Results of the computer simulation for various values of disparity: percent of correct responses as a function of the width of the square.

probably enables us to avoid some global interactions that might occur when the stimulus is relatively large in the horizontal axis. In a preliminary experiment which we performed, we presented subjects with a horizontal stripe (a wide rectangle) of variable height embedded in a RDS. We found that unlike the threshold for square size which we describe, being in the range  $8'$ – $12'$ , a stripe of height of only  $4'$  is clearly detected, and its direction of disparity is correctly perceived.

A recent study by McKee *et al.* (1995) aimed at estimating the size of the smallest correlation window that permits correct identification of disparity sign. Their stimulus was not an ordinary RDS, but rather a row of randomly-spaced dots which contained a central region of correlated dots (zero disparity). They found that Human performance was affected only when the size of the central correlated region was less than  $6'$ . The difference between this value and our results ( $8'$ ) has yet to be examined, but can probably be attributed to the different kind of stimulus used, and to the smaller number of features in the stimulus used by McKee *et al.* (1995) as compared to the RDS used in the current work.

Models of stereopsis that are based on the notion of ODC were questioned by a recent finding (Livingstone *et al.*, 1995), that showed that Squirrel monkeys, although lacking anatomically demonstrable ODC, can detect stereoscopic depth. This finding by itself indicates that the notion of ODC is not a prerequisite for stereopsis, but does not exclude models that use ODC as the neural substrate for stereopsis. The process of comparing left and right images could take many forms, since it requires only the existence of binocular cells. The design principle revealed by the ODC system might be more related to the *efficiency* of the computation, for example by using short and local fibers.

We have demonstrated that without the presence of monocular cues, stereopsis is operating in the *spatial* scale that is an order of magnitude coarser than visual acuity.

We interpret our psychophysical findings as an indication that stereopsis is an area based process, matching whole areas rather than single points. The cortical columns architecture may provide stereopsis with the area patches required to facilitate the area comparison. This would also be consistent with our findings that the minimal stimulus size for binocular fusion is inversely proportional to  $M$ , possibly pointing to a uniform cortical processing of disparity information.

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