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VERTICAL IMAGE REGISTRATION IN STEREOPSIS

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ABSTRACT: Most computational theories of stereopsis require a registration stage prior to stereo matching to reduce the matching to a one-dimensional search. Even after registration, it is critical that the stereo matching process tolerate some degree of residual misalignment. In this paper, we study with psychophysical techniques the tolerance to vertical disparity in situations in which false targets abound - as in random dot stereograms - and eye movements are eliminated. Our results show that small amounts of vertical disparity significantly impair depth discrimination in a forced-choice task. Our main results are:

a) vertical disparity of only the central "figure" part of a random dot stereogram can be tolerated up to about $3.5'$,

b) vertical disparity of the "figure + ground" is tolerated up to about $6.5'$, and

c) the performance of the Grimson implementation of the Marr-Poggio stereo matching algorithm for the stereograms of experiment (a) is consistent with the psychophysical results. The algorithm's tolerance to vertical disparity is due exclusively to the spatial averaging of the underlying filters. The algorithm cannot account by itself for the results of experiment (b).

Eye movements, which are the principal registration mechanism for human stereopsis, are accurate to within about $7'$. Our data suggest that tolerance to this residual vertical disparity is attained by two non-motor mechanisms:

1) the spatial average performed by the receptive fields that filter the two images prior to stereo matching, and

2) a non-motor shift mechanism that may be driven at least in part by monocular cues.

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Introduction

Recent attempts at building artificial stereo systems have clarified the computational problems in stereopsis. The extraction of disparity information from two images may be decomposed into two principal steps. The first step is the identification of the same object point in the two images - this is the correspondence problem for stereopsis. Julesz's (1971) experiments with random dot stereograms demonstrated that the human visual system can solve this problem even in the presence of abundant false matches and without monocular cues. The second step is the actual measurement of the disparities. Additional information and computations are of course required to convert the resulting disparity map to absolute depths. It is the first step in the computation of the disparity map - the correspondence problem - which is most difficult and it is primarily differences in approaches to its solution that distinguish the various stereo algorithms that have been proposed (e.g. Marr and Poggio, 1979; Mayhew and Frisby, 1981; Baker and Binford, 1981).

One simplification which is commonly made in the solution of the correspondence problem is based on the so-called epipolar constraint. It reduces the correspondence problem to a one-dimensional search by making use of the fact that possible matches for a point in one image lie along a line in the other image known as an epipolar line. Such one-dimensional matching schemes require, however, that the two images be precisely registered. Registration problems are introduced by simple misalignment and by differences in the imaging properties (optics and sampling grid) of the two sensors. Even when the images are globally registered, an additional complication is introduced by the geometry of stereo viewing. All of the epipolar lines are not horizontal, in general. Vertical disparities are introduced when a "horizontal scan line" search scheme is used, for example, on images obtained with convergent visual axes or when the fixation point is not "straight ahead", because the epipolar lines are not horizontal under these viewing conditions. These have proven to be serious problems for computer implementations of stereo algorithms, many of which use the horizontal scan lines of their input cameras as approximations to the true epipolar lines.

Mayhew and Longuet-Higgins (1982) have recently suggested that the vertical disparities resulting from the geometry of stereo viewing, rather than having to be "tolerated", may be used to derive information about the distance and direction of the fixation point in order to calculate absolute depth. If this idea is correct, the correspondence process should be effectively two dimensional. It should, in addition, precisely measure vertical disparity of less than $9'$ for most situations and less than $4'$ for usual stereo viewing conditions. As we will see, our results, although better interpreted in terms of a 1-D search process, do not rule out Mayhew and Longuet-Higgins' proposal.

There have been a number of other psychophysical studies of vertical disparities reported in the literature. Some of these have been concerned with measuring the vertical extent of Panum's area, that is, the range of vertical disparities that can be fused. Schor and Tyler (1981) measured the horizontal and vertical extents of

Panum's area using stimuli consisting of two spatio-temporally modulated sinusoidal lines. Both the horizontal and vertical disparity ranges for fusion vary inversely with spatial frequency. The horizontal range increases at low temporal frequencies from the static extent while the vertical range is largely independent of temporal frequency. Thus the horizontal extent decreases from about $20'$ at .1 Hz temporal disparity modulation and .125 cpd spatial disparity modulation to about $1.5'$ at 5 Hz and 2 cpd. The vertical extent decreases from about $8'$ at .125 cpd to about $1.5'$ at 2 cpd with only a slight dependence on temporal disparity modulation. Duwaer (1982) used an afterimage method to measure the non-motor component of the vertical fusion range and found a value of $8'$ to $15'$. The targets he used consisted of a 2.5^o square with or without 50 horizontal lines defining a surround 57^o in diameter. Fender and Julesz (1967) used stabilized image conditions to measure horizontal and vertical fusion ranges without eye movements. For line stimuli, they found that fusion occurred when the targets were brought within $9'$ to $14'$ vertical disparity of each other. For random dot stereograms, they found a vertical fusion range of $1'$ to $9'$.

In this paper, we study specifically the tolerance to vertical disparity in conditions in which potential false matches abound and eye movements are eliminated.

Methods

Stimuli

The first experiment was designed to explore the effect of vertical misalignment on the ability of our subjects to fuse random dot stereograms for a range of horizontal disparities spanning Panum's area. The stereograms were $54'$ square with 50% density black and white $54''$ square elements. Horizontal disparities were applied to the central 50% area ("figure") in the form of a square or diamond. Disparities were in multiples of the dot size and evenly divided between the two halves of the stereogram so that no monocular cues to depth were introduced. Stereograms were generated with $0'$, $1.8'$, $5.4'$, and $10.8'$ crossed and uncrossed horizontal disparities and $0'$, $1.8'$, $5.4'$ and $10.8'$ vertical disparities. A second set of trials used identical stereograms, but with $0'$, $3.6'$ and $7.2'$ vertical disparities. Two stereograms were generated for each vertical disparity - one with the left component of vertical disparity upward and the right component downward and one with the right component upward and the left downward. These were presented in random sequence so that subjects could not predict the direction of vertical disparity, thereby precluding compensatory eye movements. In order to obtain some indication of the factors that might influence tolerance to vertical misregistration, we used two vertical disparity conditions. In one set of stereograms, only the figure was given vertical disparity ("figure only" condition). In a second set, the figure and ground were vertically misaligned ("figure + ground" condition). There are a number of differences between these two classes of stimuli. In the "figure only" condition, there are no monocular cues to vertical disparity, only 50% of the area of the stereogram has information about the amount of vertical misalignment and no global registration process (such as eye movements) can bring the entire stereogram into registration. In contrast, the "figure + ground" condition (a) does have monocular cues to vertical disparity (the vertical misalignment of the top and bottom edges of the two halves of the stereogram), (b) 100% of the area of the stereogram gives information about the amount of vertical misalignment (possibly important for an area-based registration process) which allows (c) global registration (by vertical eye movements, for example).

The second experiment was designed to give some indication of which of the differences between the stimuli in the "figure only" and "figure + ground" conditions were responsible for the observed difference in performance. As an initial step in this direction, we removed the monocular cue to vertical misalignment by adding a border of random dots at the top and bottom of the stereograms. The stereograms were now $54' \times 65'$. The effect of this on the "figure only" condition was simply to slightly extend the background which was always at $0'$ vertical and horizontal disparity. We therefore expected no difference between the results from experiments one and two for this condition. For the "figure + ground" condition, however, we expected a decrease in performance if monocular cues were important since they had been eliminated in this experiment. The two other differences between the two vertical misalignment conditions noted above were largely unchanged. The $0'$ horizontal and vertical disparity borders were only 17% of the area of the stereogram, so a global registration mechanism would be expected to favor alignment of the rest of the stereogram. Similarly, we expected little or no difference between the first experiment and this one if tolerance were due to a purely area-based mechanism.

Subjects

Three subjects were run, two with normal acuity and one myope who wore correcting spectacles. They were highly practiced at the task. Two of them were naive about the expected experimental outcome and the third subject was one of the authors (KN).

Procedure

The random dot stereograms were generated on a LISP machine and displayed on a high-resolution, non-interlaced video monitor with P4 phosphor with a refresh rate of 60 Hz. Subjects sat in a darkened room and viewed the stereograms from 3m through two tubes which defined 1.5^{o} separate fields of view for each eye with approximately parallel visual axes. A uniform grey background with mean luminance 8.5 cd/m^2 was on at all times except during the brief presentation of a stereogram. This served three purposes: (a) to prevent eye movements occurring after presentation of a stereogram from aiding registration by erasing any phosphor persistence, (b) to maintain a state of moderate light adaptation and (c) to prevent masking artifacts by avoiding large changes in the total light flux when the stereograms were flashed. The fixation target was a $10' \times 10'$ cross centered in a $54' \times 65'$ rectangle. The order of presentation of the stereograms was randomized and the rate was controlled by the subject. Stereograms were flashed for 117 msec to preclude voluntary vergence eye movements. The display flash duration was calibrated using a phototransistor and an oscilloscope to measure the time course. After each stereogram was flashed, the subject had to make two two-alternative forced choices, each of which was indicated to the computer by pushing one of two buttons. The subject first indicated whether the figure was in front of or behind the fixation plane and then indicated whether it was a square or a diamond. The first 16 trials were practice, during which incorrect responses were signalled by a tone. Thereafter, there was no feedback. Each session consisted of the presentation of 256 stereograms and lasted about 30 minutes. Each subject had six sessions in the first experiment, and four in the second.

The data were analyzed by computing the percent of trials on which the subjects correctly discriminated the sign of depth, the percent of trials on which they correctly discriminated the forms and the percent of trials on which they correctly discriminated both depth and form. These percentages were calculated as functions of horizontal disparity for each of the vertical disparity conditions. Note that 50% correct responses represents chance performance on this two- alternative forced-choice task. Results were pooled for the two "signs" of vertical disparity since the only purpose of these conditions was to allow randomization of the direction of vertical misalignment, thereby preventing registration eye movements (performance was very similar for the two conditions). Tests for the significance of differences between conditions were conducted using the one-tailed t-test for sample means.

Computer Simulations

These results were compared with the performance of Grimson's (1981) implementation of the Marr-Poggio stereo algorithm. The binary arrays representing the stereograms were filtered with a Gaussian operator with $\sigma = 24''$ and then sampled at $30''$ intervals to model optical blur and sampling by foveal cones. They were then filtered with 3 different operators corresponding to Laplacian of Gaussian ($\nabla^2 G$) channels with central excitatory regions with widths $w = 3.6'$, $7.2'$ and $14.4'$ (see Wilson and Bergen, 1979). The stereo algorithm was run on each channel independently with "eye position" fixed at zero disparity to simulate a flashed presentation. For comparison with the psychophysical results, the disparity assignments made by the program were grouped into three pools: near, fixation plane and far.

Results

The results from the three subjects were very similar, so only averaged results will be presented (with one exception noted below). Under our experimental conditions performance on the form discrimination task ranged from about 40 to 70% correct with a very weak dependence on the experimental parameters. The relatively poor performance on this task probably reflects the small stereogram size as well as the greater difficulty of form discrimination compared with depth perception in briefly flashed random dot stereograms (see Harwerth and Rawlings, 1977). The results for both depth and form were very similar to the results for depth alone, but were shifted to a lower per cent correct level because of the poor form discrimination. We therefore only present results for the depth discrimination task.

Figure 1 shows the means and standard deviations for the collected data. Consider first the results of experiment one (Fig. 1A and B). Note that between 1.8′ and 5.4′ horizontal disparity, there is little dependence of performance on horizontal disparity for most of the vertical disparity conditions. Performance decreases at 10.8′ horizontal disparity, indicating that this value exceeds the fusion range, in agreement with published values for the size of Panum's area. The 0′ and 1.8′ vertical disparity conditions give very similar results for both the misalignment of the figure and ground (A) and the misalignment of figure only (B) cases, with nearly perfect performance. Note also that the 75% threshold is less than 1.8′ horizontal disparity, in contrast to the more than 2′ reported by Harwerth and Rawlings (1977). Data from additional experiments (not shown here) indicate that the threshold is less than 1′. There are two new features in the curves for the 3.6′ vertical disparity condition. First, when the figure and ground are misaligned there is no significant decrement in performance while misalignment of only the figure by the same amount results in a large drop in performance to below the 75% correct response threshold. Second, for the case of vertical disparity to the figure only there is a hint of a dependency of per cent correct responses on horizontal disparity so that performance improves as horizontal disparity is increased from 1.8′ to 5.4′. Performance is only slightly better than chance when the vertical disparity of the figure alone is 5.4′ or more. When the vertical disparity is given to the figure and ground, then significant impairment only occurs for values greater than 7.2′ with performance falling to chance at 10.8′.

The second experiment was designed to give some indication of the mechanism underlying the difference between the two misalignment conditions. This experiment removed the monocular cue to vertical misalignment in the "figure + ground" condition by adding borders of random dots at the top and bottom of the stereograms to fill in blank space left by the vertical misalignment of the figure and ground. Figures 1 C and D show the results. There are no significant differences between the first experiment and this experiment for the vertical disparity to "figure only" condition (Fig. 1B vs. 1D). For the vertical disparity to the "figure + ground" condition, the only significant difference (t test, $p < .05$) is for 5.4′ vertical disparity (Fig. 1A vs. 1C). Performance is at about the 90% level when there are monocular cues to vertical misalignment but falls to about the 65% level when the monocular cues are removed. One of the subjects (EH) did not show the effect, responding at about 85% correct depth discrimination for 5.4′ vertical disparity in both experiments.

In order to highlight the effect of vertical disparity, the above results have been replotted in figure 2 with vertical disparity on the abscissa. Since the data have only a weak dependence on horizontal disparity between 1.8′ and 5.4′, each data point represents the mean of the collected results for the three subjects for 1.8′ and 5.4′ horizontal disparity with its standard deviation indicated by the bars. The

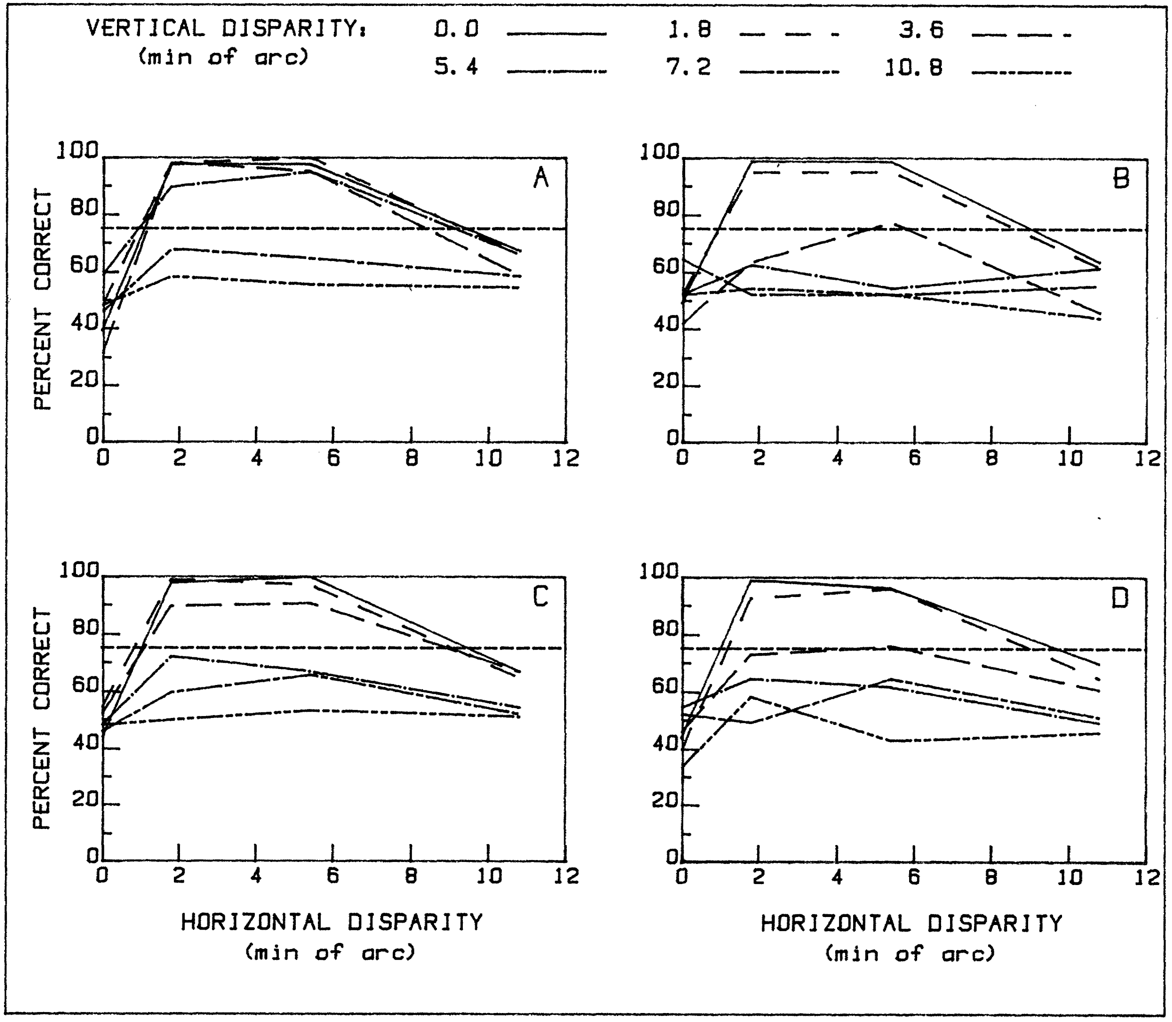

Figure 1 Mean experimental results for the three subjects. A and B present data from the first experiment. In A vertical disparity was given to the figure and ground. In B vertical disparity was applied only to the figure. C and D show the corresponding results for the second experiment where monocular cues to vertical misalignment in the "figure + ground" condition were removed. The six curves on each graph correspond to the six vertical disparity conditions as indicated by the symbol key. For each vertical disparity, there are a total of 48 trials at 0′ and 96 trials at 1.8′, 5.4′ and 10.8′ horizontal disparity. The standard deviations range from 0 to 15%. The 75% threshold is indicated by a dashed line.

results from the first experiment are shown in Fig. 2A. When only the figure has vertical disparity, performance falls to 75% correct at about 3.5′ vertical disparity, while 6′ to 7′ vertical misalignment is tolerated at the 75% level when the figure and ground are shifted. Fig. 2B shows the results for the second experiment. There is no significant difference for the vertical disparity to "figure only" condition, but maximum vertical disparity tolerated in the "figure + ground" condition is now less than 5.4′.

These results were compared with the performance of Grimson's (1981) computer

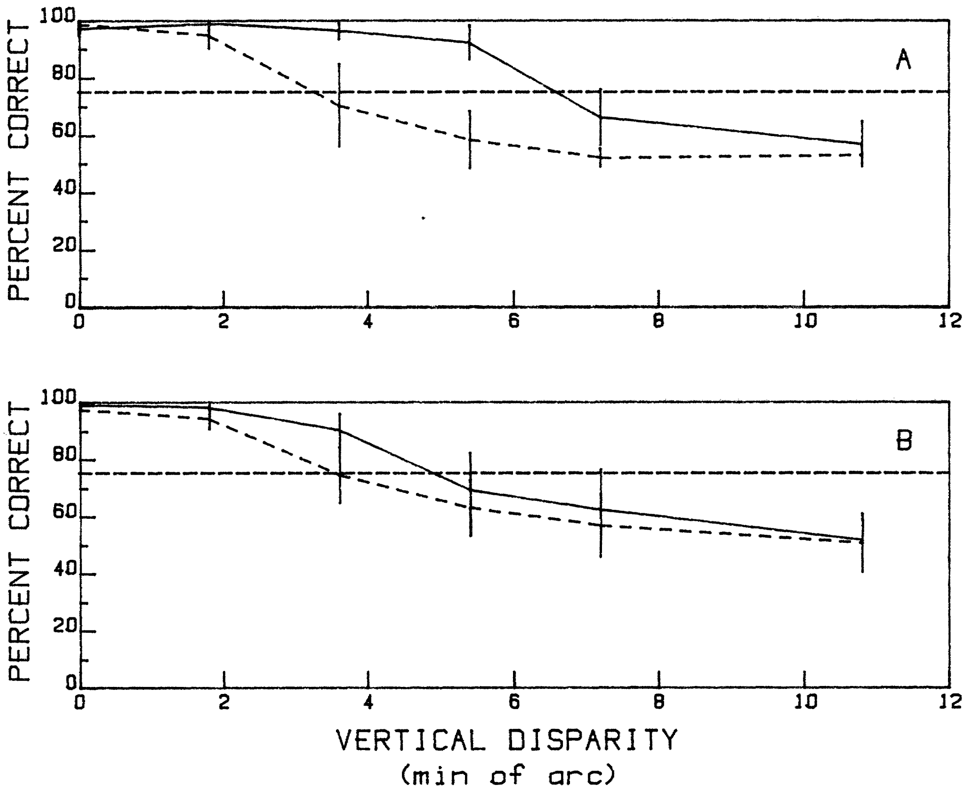

Figure 2 Data from figure 1 replotted as function of vertical disparity. Data points are means and standard deviations of the collected results from the three subjects for 1.8′ and 5.4′ horizontal disparity for each vertical disparity. A shows the results from experiment one while B corresponds to experiment 2 where monocular cues were eliminated. The solid curves are for the condition where the figure and ground are vertically misaligned. The dashed curves are for the condition where only the figure is vertically displaced. The 75% threshold is indicated by a dashed line.

implementation of the Marr-Poggio stereo algorithm for four vertical disparity conditions with 3.6′ uncrossed horizontal disparity. The disparity assignments made by the algorithm for the four vertical disparities are shown in figure 3. For ease of comparison with the two-alternative, forced-choice experimental data, the results are presented in three groupings of disparity assignments: fixation plane ±36″ ("FIX"), more than 36″ crossed disparity ("NEAR"), and more than 36″ uncrossed disparity ("FAR"). The channels are identified by the widths of the central excitatory regions (w's) of the $\nabla^2 G$ operators with which the stereograms were filtered. The values 14.4′, 7.2′ and 3.6′ were chosen as representative of a reasonable range for human foveal vision (the size of the channels is expected to increase with eccentricity, Wilson and Bergen, 1979; see also Marr and Poggio, 1979). Figures 3A-D show the results for a square-shaped form with 3.6′ crossed horizontal disparity and 0′, 1.8′, 3.6′ and 5.4′ vertical disparity, respectively. In the absence of vertical disparity, the sign of the horizontal disparity can be correctly determined from all three channels. Figure 3B shows that with 1.8′ vertical disparity, only the largest channel carries clear depth information, although the middle channel does give a weak indication of the correct disparity sign. The information on sign of disparity is much weaker, however, for the 3.6′ vertical disparity condition. A correct forced choice may be made in the 1.8′ vertical disparity case by comparing the number of assignments to the "near" and "far" pools in the larger channels. This method may still work for the 3.6′ case, but it is unlikely that the algorithm can yield correct responses for any larger vertical disparities. (A more recent version of the matching algorithm (Grimson, 1983) that exploits figural continuity is not expected to perform significantly better since the sensitivity to vertical disparity mainly depends on the properties of the filters.)

Discussion

If the vertical disparities that could be tolerated by the matching process — in the presence of abundant false matches — were large, one would be forced to conclude that human stereo matching were based on a 2-D search and significantly more complex than most existing theories assume. How large then are the vertical disparities that can be tolerated without eye movements? The answer given by our experiments is clear: under our experimental conditions, the maximum vertical disparity that allows a correct depth judgement (front vs. behind) is small ($3' - 7'$). Human stereopsis seems therefore to use the epipolar constraint and to restrict matching to a roughly 1-D search.

The obvious next question is, how is this small tolerance to vertical disparity achieved? A simple possibility is the following. Recent theories of stereo matching assume that the image is first filtered with receptive fields (with center-surround organization) of several sizes (Marr and Poggio, 1979; Mayhew and Frisby, 1981) in order to obtain suitable primitive features to be used in the matching stage. These schemes have a small, intrinsic tolerance to vertical disparity because of the spatial averaging, or blurring, performed by the filtering stages. Is this explanation consistent with our data? A comparison with a specific stereo matching scheme suggests that the results from the experiments with vertical misalignment of the "figure only" can be accounted for in this way. This conclusion is likely to hold true for several other similar stereo algorithms, since it follows more from the properties of the filters than from the matching process itself. We have in fact run an implementation of another matching scheme with the same filtering stages but which makes only near, far or approximately zero disparity measurements (Nishihara, 1983). The results were quite similar. Notice that this tolerance mechanism does not require monocular cues and is not restricted to global shifts of one image relative to the other. This proposal leads to the prediction that images that stimulate only channels with small w's will yield smaller values for the tolerance to vertical misalignment. Conversely, significant zero crossings in larger channels would mediate a larger tolerance to vertical disparity.

The additional tolerance found for the "figure + ground" case cannot be explained in the same way. The difference is small — an additional 3′ depending on the criterion used — but significant. It is also functionally important since it brings the overall tolerance to about 7′ — which is about what is required to

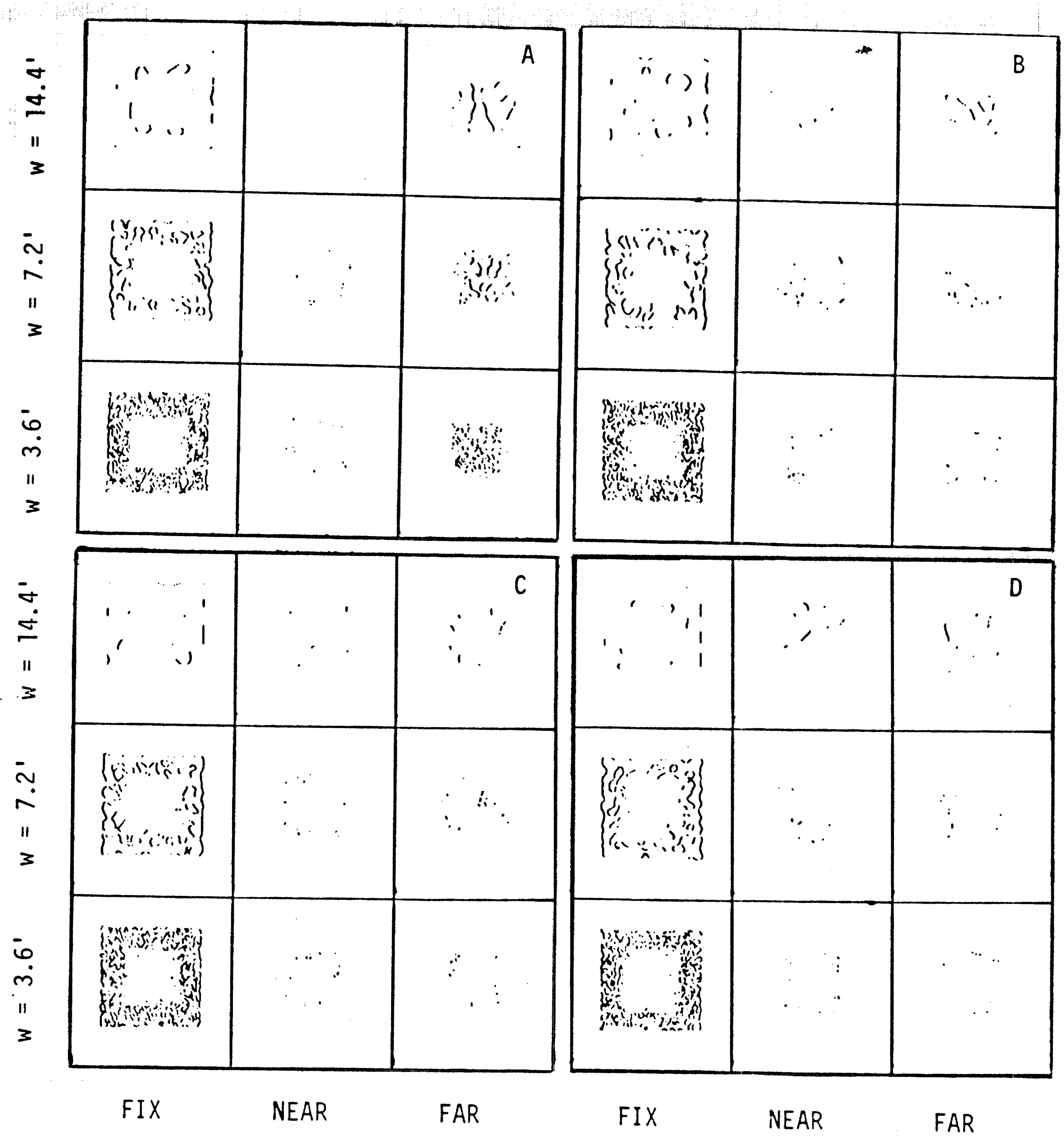

Figure 3 Disparity pool assignments from Grimson's computer implementation of the Marr-Poggio stereo algorithm. The three rows correspond to the three operator sizes used, w = 14.4′, w = 7.2′ and w = 3.6′. The three columns show assignments made to approximately zero disparity (FIX), convergent disparity (NEAR) and divergent disparity (FAR). The horizontal disparity in all the stereograms is 3.6′ divergent. A-D show results for a square with vertical disparities 0′, 1.8′, 3.6′ and 5.4′, respectively.

compensate for the vertical fixation variability of the vergence system (which is around $7' - 9'$, see also Motter and Poggio, 1983). The only obvious difference between experiments one and two is the presence of monocular cues in the first case and their absence in the second. A simple hypothesis is that there is a mechanism compensating for global shifts of the image, possibly driven by monocular cues. The second experiment confirms that monocular cues have a significant role in the additional tolerance to vertical disparity (Fig. 2A vs. 2B). One of the three subjects (EH), however, does not show the effect, indicating that there may be individual variability in the strategies used to compensate for binocular distortions.

The properties of the correction mechanism would be very similar to eye movement properties and one wonders whether eye movements may indeed play a role. We believe that this is unlikely because of the short exposure time we used, since the reported latency of vergence movements of this small size is significantly slower (Schor and Ciuffreda, 1983). But this possibility cannot be completely excluded, since we did not record eye movements. The discovery that directed, corrective vergence movements were possible within a time interval of less than 120 msec would be surprising. If we assume that this is not the case, we are left with the intriguing idea that a shift mechanism, independent of eye movements (possibly cortical), may underlie the residual $3'$ tolerance to vertical disparity. Notice that $3'$ disparity corresponds to about 6 foveal cones, a small but non-negligible disparity. In the light of increasing evidence for a "focus of attention" in monocular visual information processing capable of moving across the visual field (Posner, 1980) a "shift" mechanism for vertical disparity may not be too far-fetched. Notice that, despite the term, no real shift of one image in the cortex or elsewhere needs to take place.

Our experiments do not provide any clue to what drives eye movements in normal conditions and to which vertical disparities and vertical disparity gradients can be eliminated by eye movements. The simplest hypothesis consistent with available data is that eye movements guided by monocular cues correct for vertical disparity. An observation made during our experiments also supports this point of view. In the case of vertical misalignment by more than $3.6'$ of only the figure, where there are no monocular cues, prolonged viewing time does not significantly improve depth discrimination. The stereograms remain very difficult to fuse. However, in the case of vertical misalignment of the figure and ground, where there are monocular cues, fusion occurs effortlessly and under prolonged viewing conditions the subject is not aware of the vertical disparity. In the third condition, where the figure and ground are vertically misaligned but the monocular cues are eliminated by adding a random dot border, prolonged viewing gives rise to alternating percepts. The dominant percept is rivalrous, but occassionally the figure and ground are fused and can be seen clearly. These moments of fusion probably occur when the shifts in eye position which accompany binocular fixation align the stereograms by chance.

Several points should be kept in mind in interpreting our data and our conclusions. First, our experiments are strictly foveal since the overall area of the stereograms is slightly over 1^o square. It is likely that larger stereograms may yield larger tolerances. We think, however, that the differences will not be dramatic and may be fully explained by the effect of eccentricity (cone spacing doubles at 4°) and by the improved signal-to-noise ratio in detecting the relative number of *near* vs. *far* matches over a larger area. Second, it may be argued that our forced-choice test results in an over-estimate of the effective tolerance to vertical disparity. This is because vertical misalignments of the visual axes of the two eyes at the onset of the stimulus are expected to increase the range of vertical disparities that yield more than 50% correct responses beyond the actual fusional range. This effect is limited, however, to a range between 50% and 75% correct responses. Our estimate of vertical disparity tolerance, however, refers to a criterion of at least 75% correct responses. Third, form is barely recognized at all in our conditions, even without vertical disparity, possibly an indication that full stereo matching is not achieved. There may be several reasons for this: the size of the stereogram may be too small and the exposure time too short. Additional experiments should clarify whether a process specialized for the detection of form needs a longer time than the 117 msec available in our experiments between onset of the stimulus and onset of the "masking" pattern. In any case, it is worthwhile to stress that our experimental conditions uncover only one aspect of stereopsis, responsible for relative depth discrimination.

Finally, additional experiments are necessary to characterize the possible role of vertical disparity. For instance, it would be important to repeat our experiments at different fixation distances with the kind of vertical disparity and deformations that are associated with perspective projection. It may well be that the system easily corrects for them from extraocular information about fixation distance. Alternatively, the visual system may recover depth directly without the need of extraocular information, as proposed by Mayhew and Longuet-Higgins. In this case, vertical disparity should be not only tolerated but also precisely measured.

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