Stereogram design for testing local stereopsis

Gerald Westheimer and Suzanne P. McKee

The basic ability to utilize disparity as a depth cue, local stereopsis, does not suffice to respond to random dot stereograms. They also demand complex perceptual processing to resolve the depth ambiguities which help mask their pattern from monocular recognition. This requirement may cause response failure in otherwise good stereo subjects and seems to account for the long durations of exposure required for target disparities which are still much larger than the best stereo thresholds. We have evaluated spatial stimuli that test local stereopsis and have found that targets need to be separated by at least 10 min arc to obtain good stereo thresholds. For targets with optimal separation of components and brief exposure duration (250 msec), thresholds fall in the range of 5 to 15 sec arc. Intertrial randomization of target lateral placement can effectively eliminate monocular cues and yet allow excellent stereovision. Stereoscopic acuity is less seriously affected by a small amount of optical defocus when target elements are widely separated than when they are crowded, though in either case the performance decrement is higher than for ordinary visual acuity.

Key words: stereoscopic acuity, local stereopsis, global stereopsis, optical defocus

A subject is said to have stereopsis if he can detect binocular disparity of retinal images and associate the quality of depth with it. In its purest form this would manifest itself by the ability to identify a single feature, e.g., a line, as appearing in front of one or more other features when it differs from them in having crossed disparity of its retinal images as compared with those of the other features. Insofar as differing values of the "depth" quality can be associated with single and quite small individual features, it is appropriate to use the term local stereopsis. Disparity thresholds under such circumstances are very low indeed, certainly under 10 sec arc in a good observer, and such low values can be attained with exposures of half a second or even less.

It is sometimes thought that an observer can correctly call the direction of depth of a feature by merely inspecting the two eyes' views of a pattern containing disparity without truly experiencing the depth sensation that disparity normally engenders, although in fact stereopsis can result from binocular pattern differences that are too small to be detectable in one or the other monocular retinal image.1

For that reason, random dot stereograms have been devised which have the property of containing no depth clues that are accessible to monocular viewing. There are many identical feature elements which can have their retinal images associated in a variety of ways, each of which would yield a different disparity for each element. For a particular set of such associations, a pattern is seen in

From the Department of Physiology-Anatomy, University of California, Berkeley.
This research was supported by the National Eye Institute, U. S. Public Health Service, through grant EY-00220.
Submitted for publication March 29, 1979.
Reprint requests: Dr. Gerald Westheimer, Department of Physiology-Anatomy, University of California, Berkeley, Calif. 94720.
Stereogram design for testing local stereopsis

Fig. 1. Diagram of one line of a random dot stereogram. Central portion (elements 5 to 14) of the pattern of the left eye has been shifted one element to the right to create a disparity between the two eyes. For some elements, e.g., element 8', there is ambiguity about the direction of the disparity because that element could be associated with element 8 or element 10 of the pattern seen by the other eye.

The very content of global stereopsis, however, entails some disadvantages for random dot stereograms: some observers with normal local stereopsis have difficulties making depth judgments in them; the structure of these patterns limits the minimum disparity that can be presented to values considerably above the best stereoacuity thresholds found with simpler patterns, and unless the presented disparity is quite large (>2 min arc), a long exposure duration is usually required for a sensation of depth.

In Fig. 1 the structure of a small region of a random dot stereogram is analyzed to illustrate how the need to scramble outlines of the global pattern imposes restrictions on the placement of elements. A line of 18 elements, each of which can be either white or black, is shown in the views of both the right and left eye. Where no disparity is intended to be present, the patterns of the two eyes are in exact register (squares 1 to 4, 15 to 18).

A disparity equal to one square is produced by displacing squares 5 to 14 to the right in the left eye—here exact register is attained by association of each element in the right-eye view with the immediately adjacent one to its right in the left-eye view.

The three important features of this arrangement are as follows:

1. There is ambiguity. Element 10 in the right eye has no counterpart in the left eye. It can be associated with element 8' or 10' in the left eye, each giving a binocular disparity (in comparison with the reference regions 1 to 4, 5 to 18) but in opposite directions. The global percept is attained by favoring the association 10 → 10' because a similar association of the other elements produces least overall dissonance.

2. There is crowding. For the purposes of associating right and left eye features to determine the disparity, elements or clumps of elements must appear separate from their neighbors. The minimum separation is one element size, and this suffices if it is about 1 min arc or more. The average separation will depend on the element size and the statistics generating the pattern; when the probability for black squares is 0.5, then if any separation exists between elements, the mean separation will be two elements.

3. There is a restriction on stimulus disparity. In the arrangement shown in Fig. 1, which is the most common one used, disparity can be created only in modules of the size of each element.

The essence of a random dot stereogram is not the irregular placement of elements. Randomly placed features, each with a clearly and essentially unique disparity, can produce excellent stereopsis, as has been shown by Frisby and Julesz and as will be demonstrated below. The task of making a depth pattern inaccessible to monocular viewing by creating multiple ambiguities of element pairing, which is the hallmark of a true ran-
dom dot stereogram, calls for the elaboration of a global percept, a facility which is not necessarily the subject of a first examination of a patient’s visual function.

In this paper we point out some aspects of stereoscopy that help account for the large differences in threshold parameters between random dot stereograms and more traditional stereoacuity patterns. In the light of these we have designed stereograms that, like the random dot patterns, are inaccessible to purely uniocular judgments while at the same time demonstrating stereoscopic acuity in the range of a few seconds of arc.

**Methods**

Targets were created under computer control on two 602 Tektronix units with the P4 phosphor, whose screens were superimposed by a beamsplitting pellicle. Suitable placement of polaroid filters in front of the oscilloscopes and the two eyes guaranteed that only one screen was visible to the left eye and the other screen was seen only by the right eye. Target luminance was about 20 mililamberts. During an experimental session, a target was displayed every 3 sec for a duration, usually, of 500 msec. In the intervening period, there appeared a fixation square which was not visible during target presentations. The fixation square, outlined by four brackets 0.75° apart, permitted good binocular and foveal fixation. Subjects sat 2.5 m from the screens; observation was always binocular with natural pupils and with optimal correction for that distance of any refractive error.

The target elements for all these experiments were small bright squares, 2 min arc on a side. The “test” target elements were presented with one of seven possible disparities, three equally spaced positions (usually 8, 16, and 24 sec arc) behind or in front of the fixation plane and one in the fixation plane. Reference elements were always presented in the fixation plane. The subject's task was to identify the direction of the test element disparity (“front” or “back”) by setting a switch. A small

---

**Fig. 2.** Threshold disparity (sec arc) for stereoscopic depth discrimination as a function of edge-to-edge separation of two small squares, 2 min on a side. • •, Horizontal separation between the two squares; a a a, vertical separation. Exposure duration 500 msec. Subjects G. W. and J. S. give consistently better thresholds for one direction than the other.
flash appeared if the choice was in error. Three hundred responses were collected for each threshold; the disparity at which the subject could correctly respond on 75% of presentations, as well as a standard error of this value, was determined by probit analysis of the psychometric function. Whenever values of parameters are being compared in this paper, the relevant results were obtained in interdigitated form that factored out the important interacting variables of training, fatigue, etc.

Results

In the first experiment, we examined the effect of target placement on stereoscopic acuity for a very simple stimulus: two small squares. Separation, i.e., the distance between the nearest sides of the target squares, was investigated in both the horizontal and vertical directions. The results, illustrated in Fig. 2, demonstrate that stereoscopic acuity was optimal for only a narrow range of target separations, 10 to 20 min arc, and showed a decrement when the separation was widened or narrowed beyond these values. These results are in good accord with the determination of stereoscopic acuity as a function of separation for other targets, principally lines. The use of small target squares rather than vertical lines has also permitted us to point out that some observers gave a consistently better performance for separations in one direction than in the other.

The next experiment demonstrated even more tellingly how target separation can affect stereoscopic acuity. Dimensions and stimulus parameters were the same as experiment 1, but now the test target was completely surrounded by identical comparison targets instead of merely being flanked by one. The pattern consisted of a 3 by 3 matrix of 2 min arc squares, and only the center one was shown with disparity. In Fig. 3, disparity thresholds are plotted as a function of the distance between facing sides of tests and reference squares; for comparison, the data for horizontal separation from experiment 1 have been replotted in this figure. Obviously the presence of additional reference targets degraded stereoscopic acuity at small target separations, for the threshold rose quite precipitously when the targets were crowded to distances less than 10 min arc.

It is clear from Figs. 2 and 3 that if a minimum value of stereoscopic depth threshold is desired, the targets have to be at least 10 min arc apart. In a random dot stereogram, unfortunately, this size of grain would be too coarse and would defeat the purpose of threshold determination.

On the other hand, if the aim is to point to an effective test of local rather than global stereopsis, these data constitute a helpful
Fig. 4. Diagram of 7 by 7 matrix showing typical amount of randomization of horizontal and vertical placement of target elements. Diagram drawn to scale for a mean separation of 10 min. For each target presentation, the position of each small 2 min square was varied about the mean value. Central submatrix of 3 by 3 elements, outlined here for diagrammatic purposes, was shown with a disparity between the two eyes. No outline was present in experimental target configuration.

guide to pattern design. Once the individual features making up a stereogram are placed at this optimum separation, a new strategy has, however, to be devised to prevent the detection of the direction of disparity in a monocular view. One such approach is described here.

The pattern was made up of a 7 by 7 matrix of individual features equally spaced horizontally and vertically. Again, we used a small square 2 by 2 min arc for the individual components, but this is not critical. Although most of the matrix elements remained in the plane of the fixation square, the center 3 by 3 submatrix was shown with a disparity, i.e., was presented with a displacement in opposite directions in the two eyes relative to the remainder. As before, the parameter of interest was the separation of the matrix elements. When seen in this way, the subject had to judge whether the center submatrix appeared in front or behind the surrounding matrix elements. A sophisticated observer could, however, make correct responses by using only one eye and noting whether the center submatrix was laterally displaced to the right or left. This is not as serious as it sounds, since it would require considerable

Fig. 5. Threshold disparity (sec arc) for stereoscopic depth discrimination using random patterns of the kind illustrated in Fig. 4, plotted as a function of mean center-to-center separation between adjacent target elements. Separation of elements could vary horizontally and vertically by up to ± 3.2 min about the mean separation. The data found with this target are very similar to the data found for regular 3 by 3 square matrix (Fig. 3).
sophistication to figure out what the examiner called a correct response and also because, as we have shown in an earlier paper, the threshold for lateral displacement detection is several times higher than that for disparity detection at separation values greater than 8 min arc.

However, to forestall most difficulties in this direction we introduced a scrambling system similar to procedures which were frequently used in other research (e.g., Blake-more) to mask monocular cues. In our procedure, each small square was displaced from its centered position randomly either up or down and also either right or left by one of three randomly chosen amounts. A sample pattern is shown in Fig. 4. Each target element, including the elements of the central test matrix, could be in one of 49 positions in a 7 by 7 array. We chose 32 sec arc as the basic “jitter” module, so that each target element appeared at random either centered on the position given by the regular spacing of the square matrix as a whole, or 32, 64, or 96 sec arc to the right or left and also a similar distance above or below the mean position.

In this way the separation of individual elements was not fixed but varied about some mean value ±3.2 min arc. The patterns were generated on-line on the two Tektronix units by a program utilizing about 10,000 words of the core memory of a PDP-11/05 computer. Random generators and tables were included in the program to ensure that during every presentation each pattern element was shown with a new and different horizontal and vertical jitter. Thus, on each target presentation, a completely new arrangement of the 49 squares appeared before the subject’s eyes. To test the disparity threshold, the whole pattern was shown for a 500 msec duration, the central submatrix of 3 by 3 elements being given at random one of an ensemble of seven disparities—no disparity or one, two, or three modules of either crossed or uncrossed disparity. Fig. 5 shows the threshold disparity found with this pattern, here plotted as a function of the mean center-to-center distance between adjacent target elements. Even in this most compli-

---

**Fig. 6.** Ring targets made of nine squares (2 min on side). Central element (shaded for diagrammatic purposes) shown with disparity. In addition, mean binocular placement of central element can be randomized trial-by-trial to mask monocular information about disparity. Feedback given for both conditions. Stereo thresholds: Minimum discriminable binocular disparity (sec arc), measured when there was intertrial randomization of lateral position of central square in range of ±1.6 min arc for a ring diameter of 36 min. Unocular thresholds: Identical stimulus conditions and scoring, but both eyes viewed target seen by left eye during stereo presentation. Because threshold value is now eight to 20 times higher than under stereo conditions, this kind of target is highly effective in making the disparity cue unavailable to monocular viewing.

Cated of stimulus patterns, the underlying function relating stereoaucity to target separation appeared to determine these thresholds. It should be noted that these thresholds were, under optimum conditions, as low as those found with patterns presented in a regular, nonrandom, arrangement such as the square 3 by 3 matrix of Fig. 3.

Our intent to create a test of local stereopsis without consistent monocular information, an intention which led us to design the random pattern of Fig. 4, can, however, be realized in a somewhat less heroic manner. The guidelines we followed were (1) the avoidance of feature crowding by maintaining an average separation on the order of 10 to 15
### Table I. Threshold for detection of depth of central element of ring target (Fig. 6), presented for 250 msec

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Threshold (sec arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. R.</td>
<td>15.3 ± 1.5</td>
</tr>
<tr>
<td>S. Y.</td>
<td>12.9 ± 1.2</td>
</tr>
<tr>
<td>G. W.</td>
<td>9.6 ± 0.9</td>
</tr>
<tr>
<td>S. M.</td>
<td>5.4 ± 0.5</td>
</tr>
</tbody>
</table>

**Fig. 7.** Stereoscopic acuity and visual acuity with a small amount of defocus. Stereoscopic depth threshold (sec arc) measured with ring target shown in Fig. 6, target element separation of 6 and 18 min arc. Visual acuity measured by Snellen letters and converted to minimum angle of resolution in minutes of arc. Subject G. W. wore his correction and results are shown with and without an additional +0.5D lens binocularly. Subject S. M. is about +0.5D hyperopic with good accommodation and results are shown wearing either no lens or a +1.25D lens binocularly.

- **min arc** and (2) the masking of the uniocular information about lateral position which is inherent in the presentation of any feature with binocular disparity. Fig. 6 shows a pattern substantially satisfying these guidelines which is also more suitable for administration to an unsophisticated population of patients and test subjects. It consisted of a ring of eight features with a “test” feature in its center. We have used 2 by 2 min squares for the individual elements, but other features could be used. The important dimension of the stereogram was the edge-to-edge separation of the individual features; in this pattern we set the mean distance between the central test feature and the surrounding ring at about 18 min arc by giving the inside horizontal diameter of the ring a value of 36 min arc. The center feature was given a disparity with respect to the outer ring, and the subject had to respond whether he judged it to be in front or behind the plane of the ring. To obscure the lateral position information available in a purely monocular view, the mean binocular position of the center feature was given a random jitter in the horizontal direction—the feature was shown at random in one of seven mean binocular positions: centered or one, two, or three distance modules (module size 32 sec) to the right or left of center. The direction of decentration of the center feature in a uniocular view was no clear cue to the direction of its intended disparity. That such a scrambling system can act quite satisfactorily to separate out the disparity judgments from lateral placement judgment was demonstrated in the data of Fig. 6. Shown are thresholds for (1) depth discrimination and (2) lateral displacement discrimination for three subjects. The parameters of duration, distance, amount of scramble, etc., were identical for both thresholds; the first was obtained by the usual stereoscopy procedure, the second by having the subject view with both eyes only the view of the left eye of the stereoscopic target and still signal as errors.
those responses in which a crossed disparity presentation was called "behind" and an uncrossed one "in front."

We used this test for local stereopsis under conditions in which decrements in performance were to be expected. One of these conditions was exposure duration. Ogle and Weil\(^\text{11}\) have demonstrated the falloff of stereoacuity with decreasing duration. Although Julesz\(^\text{12}\) observed good global stereopsis with tachistoscopic observation (50 msec) of his random dot stereograms, they had a disparity of 20 min arc. Harwerth and Rawlings\(^\text{8}\) found that a 250 msec exposure gave essentially chance responses for random dot stereograms with 4.5 min arc disparity or less. Our stereograms for testing local stereopsis, on the other hand, had only slightly elevated stereoacuity thresholds for 250 msec exposures. The results (without the random jitter) on four subjects still gave stereo thresholds in the range of 5 to 15 sec arc for this duration (Table I).

Random dot stereograms and all other patterns that involve small feature separations might in addition be highly susceptible to the detrimental effects of optical blur because this reduces the effective separation of features and, in fact, can produce overlap of contours of features whose disparity has to be detected. In Fig. 7 we show the stereoacuity measurement with our ring target in two sizes with a spectacle blur that reduced ordinary visual acuity (as measured by Snellen letters) by a factor of less than 2. Surprisingly, the stereoacuity was more severely affected even for a mean target separation that retained clear identity of all features under blur. For smaller target separations, however, the drop-off of stereoacuity can be disastrous.

Discussion

If the primary objective of a test is the measurement of local stereopsis, then the complexities introduced by random dot stereograms may actually impair stereoacuity, particularly for short durations. The major virtue of random dot patterns is that their design can totally obscure monocular cues. We have shown that less extreme schemes can also minimize monocular detection. The introduction of random jitter in the horizontal placement of test elements makes it unlikely that a subject could imitate good stereoacuity by closing one eye. In the various clinical and experimental situations calling for tests for the presence and acuity of stereopsis, the procedures described in this paper are in our opinion preferable to random dot stereograms because they do not allow recognition of the presence of local stereopsis to be obscured by failure to achieve a global percept. The more basic mechanism of local stereopsis has a faster time course and finer grain and more clearly emerges in the direct mode of addressing outlined here.

REFERENCES