

Interpolation in stereoscopic matching

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Anyone who has stared at a repeating wallpaper pattern, or a periodic pattern of tiles, has probably experienced the phenomenon of a false stereoscopic depth percept. This arises because of a mismatching in the two eyes of repeating elements in the pattern. The phenomenon is less likely to occur if an edge of the textured region is in view; the edge seems to fix the registration of elements. We describe here a stereogram which exemplifies this principle; it has a central, periodic region bounded on either side by edges with pre-assigned disparities. We find that the perceived depth of the central region is controlled by the edges. In certain conditions (when the period is spatially large), the edges simply impose one of the expected discrete matchings. In other conditions, however, we observe a striking phenomenon: interpolation in depth occurs between the edges, violating any possible feature-by-feature matching.

Our stereogram can be broadly described as a regular grid of points with horizontal disparities introduced at the two vertical edges (Fig. 1A). A single row from the grid is shown in Fig. 1B, where the convention is that the vertical alignment of the dots seen by the left and right eyes corresponds to the zero disparity; that is, if each dot were matched to that vertically above or below, they would be seen in the fixation plane. The row consists of a set of equally spaced dots, typically 6 arc min apart, but with the left-most dot moved inwards a certain fraction, S_L , of the inter-dot spacing in the left eye, and the right-most dot moved inwards by a fraction S_R of the inter-dot spacing in the right eye.

The stereoscopic percept depends on how points in the two eyes are matched. When the stereogram is inspected carefully, using a large inter-dot spacing (for example, Fig. 2 viewed close up), one of two possible percepts is seen, depending on the size of S_L and S_R . When S_L and S_R are small, the percept corresponds to the matching shown in Fig. 1C(1), and consists of a plane with two flaps tilted forwards at the edges [Fig. 1D(1)]. When S_L and S_R are large, the underlying matching is that of Fig.

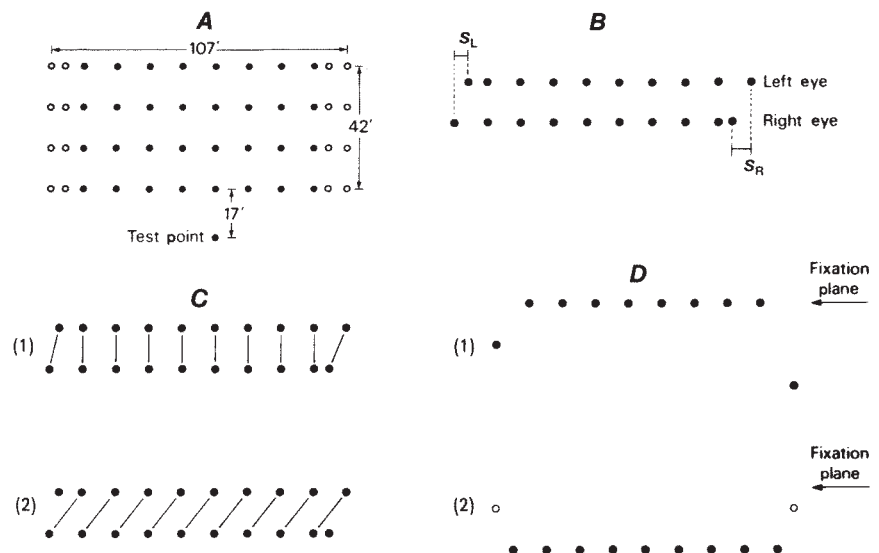
1C(2), in which each point is paired obliquely; the percept here is of a grid lying in front of the fixation plane, with two unpaired points at the edges [Fig. 1D(2)]. Thus, changing S_L and S_R causes a change of matching throughout the central regular lattice. Such propagation of matching from a limited area throughout a periodic region has been shown to occur in stereograms studied by Julesz and Chang¹, of which ours can be regarded as a highly specialized case.

To explore the depth percepts more systematically, we added a test point beneath the grid (Fig. 1A) and asked subjects, in a forced-choice paradigm, to judge whether the test point lay in front of, or behind, the grid. The test point was placed at a fixed vertical position below the grid, and could be given any desired horizontal location, so that depths of particular regions of the grid could be explored. The test point was randomly given one of seven equally spaced disparities, chosen so that at one extreme the grid lay considerably in front of the test point, and at the other, behind it. By fitting a cumulative gaussian curve to the percentage of trials on which the grid was reported as lying in front of the test point, we could locate the apparent mean position of the region of the grid above the test point, and also determine the standard deviation in its perceived position². Observers were first shown a fixation pattern which disappeared during the subsequent 160-ms presentation of the grid and test point.

When the (horizontal) inter-dot spacing in the central region was $>6-8$ arc min, we found that the grid lay either in the fixation plane [as expected according to Fig. 1C(1)], or moved forward to the depth expected of the oblique matching in Fig. 1C(2). The former was seen when the sum of the displacements, $S_L + S_R$, was small (<1 inter-dot spacing), and the latter when the sum was large (>1.5 inter-dot spacing). For intermediate values of the sum $S_L + S_R$, either depth percept might be seen on a given trial, with a probability depending on the sum $S_L + S_R$.

A radically different type of behaviour was seen when the inter-dot spacing was <6 arc min; it was then possible to obtain depth percepts which could not be accounted for by any discrete matching of points. For example, Fig. 3A shows a depth profile of a grid with $S = 0.2$, $S_R = 0.8$. This profile is slanted in depth: it runs continuously between the depths which would be expected from matching the end points (open circles), and none of the intermediate values is compatible with discrete pairings of points within the grid. It is as though the end points have been paired and the intermediate depths obtained by interpolation between these extremes. For comparison, Fig. 3A also shows profiles for $S_L = S_R = 0$ and $S_L = S_R = 0.67$; both of these are

Fig. 1 A, The grid of our stereogram, showing the test dot. B, A single row from the grid, with the left-most dot in the left eye displaced inwards by a fraction S_L , and the right-most dot of the right eye displaced by a fraction S_R of the inter-dot spacing. C, (1), (2), Two possible matchings of points of the left and right eyes in a single row. In (1) the dots are matched in sequence; in (2) the displaced dots at the ends of each eye's row are unmatched, and a point in the left eye is matched to a point in the right eye which is one step of the grid to its left. D, The depth percepts expected, based on conventional stereoscopic theory, from the matchings (1) and (2). The fixation plane (vertical matching in C) is indicated by an arrow. In fact, a fixation target was always presented before the grid was shown, but was never shown simultaneously with it. In (1), two dots lie in front of the fixation plane. Here S_L is shown smaller than S_R , so the right-most dot should be farther in front than the left-most. In (2) the grid lies in front of the fixation plane (corresponding to a crossed disparity). The two monocular points (open circles) appear to lie behind the grid, although we do not know precisely what perceived depth should be assigned to them.



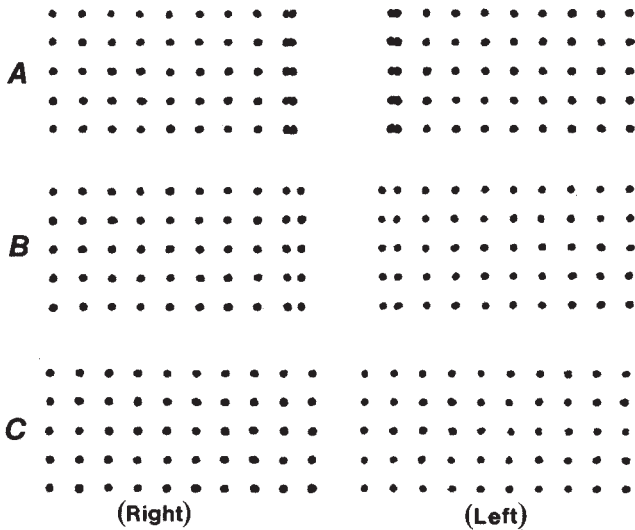


Fig. 2 A stereogram of grids (with dimensions somewhat different from those in Fig. 1A) to show the basic phenomena. The displacements S_L and S_R are equal: they have a large value in panel A and are zero in C. In B, a displacement has been chosen which should give an intermediate depth percept under interpolation conditions. Those who free-fuse by converging will see the grid correctly; those who diverge will see the depths reversed. When the stereogram is viewed quite close up (say 1 m), the discrete matchings of Fig. 1C and D should be seen. When it is viewed from a distance of ≥ 3 m, the inter-dot spacing comes within the interpolation range (< 6 arc min), and B should appear at a depth between that of A and C.

flat, the former being close to the fixation plane, and the latter forward of it, though not as far forward as would be expected for the oblique matching.

These intermediate-depth percepts do not correspond to an ambiguous alternation between the two matchings, as demonstrated by the curves showing the proportion of trials in which the test dot lay in front of the grid, as a function of test dot disparity (Fig. 3B). If there were an alternation of percepts, these curves would be broad, encompassing the range from the fixation plane to the forward matching. However, they are very narrow, having a standard deviation of 10–15 arc s. The intermediate depths (such as curves b–d in Fig. 3B) are, in fact, as well localized as the extremes (curves a, e) which satisfy a ‘conventional’ matching. Depth percepts which lie between possible discrete matches have been described by Foley³, and may be related to those we find, but his conditions were very different from ours, and the intermediate states far less localized.

Interpolation appears to be quite stable under prolonged inspection (for example, Fig. 2 viewed at ≥ 3 m), and, in particular, the percept does not depend on vergence. The viewing time of 160 ms used in our experiments was designed to eliminate changes of vergence during each presentation. In one experimental condition, the displacements S were changed randomly from trial to trial to prevent the observer from maintaining a biased convergence position in front of the fixation plane, and essentially similar results were obtained.

One might attempt to account for interpolation by saying that the stereo matching system has a coarser resolution than 6 arc min, and ‘sees’ only the ends of the grid when the inter-dot spacing is small. We can show that this is not the case by randomly perturbing points in the periodic region by the same amount in each eye; when this is done, the grid can be matched as a flat surface in the fixation plane (Fig. 4A), but the oblique matching should introduce disparity variations (Fig. 4B). There are general arguments for expecting that the matching which gives the more continuous depth profile will be preferred⁴ and, indeed, even quite small random perturbations keep the grid in the fixation plane matching Fig. 4A, no matter how large the displacements S . For example, for an inter-dot spacing of 3.7 arc min, a 20-arc s (SM) or 40-arc s (GM) perturbation serves to

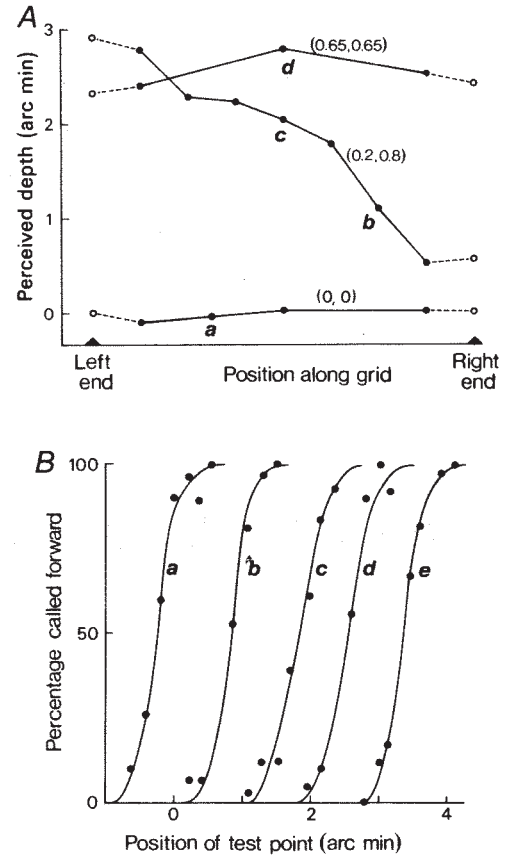


Fig. 3 A, Apparent depths for various values of S_L and S_R (shown in brackets) at selected positions along a grid of inter-dot spacing 3.7 arc min (test subject G.J.M.). Each solid point represents the mean of a psychometric curve (see B) based on at least 200 trials. The open circles show the expected depths of the paired end points of the grid, calculated from their disparities. B, Psychometric functions for various points in A (curves a–d) and for the grid with $S_L = S_R = 1$ (e). The ordinate shows, for a given disparity of the test dot, the percentage of responses ‘test dot in front of grid’. If a cumulative gaussian is fitted to these points using the probit method², its mean defines the apparent depth of the grid, and its standard deviation indicates the imprecision of this depth judgement.

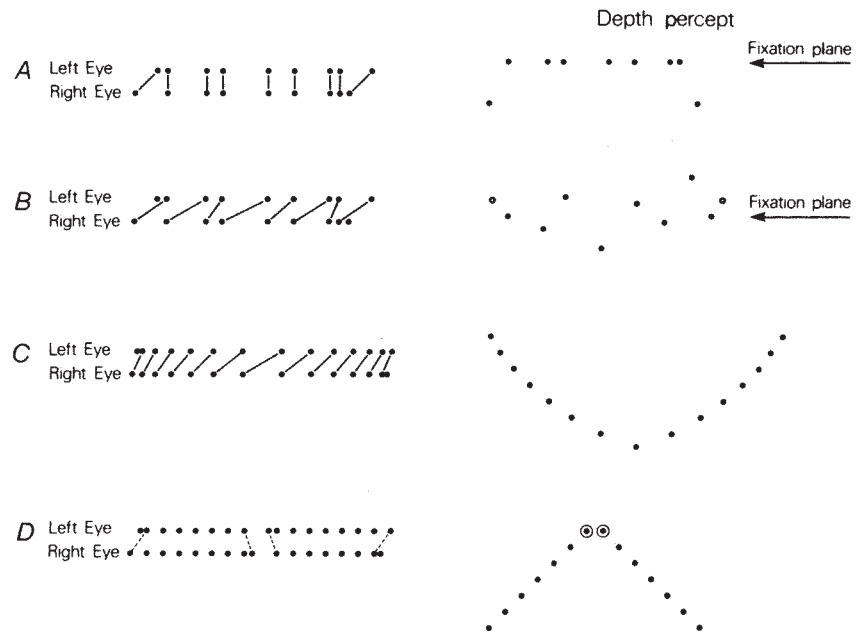
keep the grid in the fixation plane, even with the largest possible values of S_L and S_R . Stereoscopic matching is therefore sensitive to very small perturbations of the points in the grid.

What is the relationship between interpolation and the conventional point-by-point matching seen for larger dot spacings? To determine how they interact, we constructed a grid which expands slowly so that the spacing in the centre is in the range where discrete matching occurs, while the spacing at the edges lies well in the interpolation range (Fig. 4C). A displacement at the edges brings forward the whole grid, generating a vivid arch in depth. This implies that interpolation is not merely an interpretative stage which supplies appropriate depths after matching is complete, but can influence matches, as in the central region here.

We have seen that the edges of the grid have a privileged role in that they provide end points for interpolation. What counts as an edge? If we displace two dots in the centre of our grid, so making a small gap, the resulting percept exhibits two segments of interpolation (Fig. 4D), suggesting that the inner gap provides two ‘edges’ in this sense (dotted lines).

In summary, the stereo matching system appears to skip over regions with a periodic spacing of < 6 arc min, but is alert to small irregularities within such a region. These irregularities might be interpreted either as gaps or as disparity discontinuities. Of the two possibilities, the second is the more attractive; it implies that it is not periodicity *per se* which is required for

Fig. 4 A, In a modified version of the stereogram, a grid is constructed from several identical rows such as that shown here. This row is derived from that shown in Fig. 1B by leaving the outer two dots in each eye unchanged, but randomly perturbing the inner dots by the same amount in each eye. The lines show the matching which corresponds to Fig. 1C(1), and the depth percept is shown to the right. This is found for all dot spacings in the interpolation range (<6 arc min). **B**, An oblique matching, corresponding to Fig. 1C(2), in which each dot in the left eye is matched with a dot one further along in sequence in the right eye; this generates a ragged depth profile (shown on right). **C**, A modified version of the row shown in Fig. 1B. The spacing between dots at the edges is 3 arc min; this spacing increases gradually towards the centre, reaching a maximum of 11 arc min, and then decreases again, in a symmetrical fashion. The expected depth percept for the oblique matching shown is a forward-bending arch. **D**, A gap is created by displacing two dots near to the centre of the grid. In the left eye, a dot is moved half an inter-dot spacing to the right; in the right eye, the dot which would be paired with this in the fixation plane is moved to the left by the same amount. With the dot spacing in the interpolation range, two segments of interpolation are seen (shown on right). The fine broken lines indicate the matching which defines the 'edge'. In fact, the perceived depth of these dots is somewhat variable between trials, and this is indicated by ringing of the dots in the diagram of the depth percept.



interpolation, but simply the absence of disparity discontinuities. There is an obvious economy in making explicit matches only where a potential disparity discontinuity is registered.

These findings impose some constraints on models of stereoscopic matching. For example, the fact that disparities at the edges determine the matching within each grid in the absence of vergence movements argues against the coarse-to-fine vergence strategy postulated by Marr and Poggio⁵. Information might, in principle, be propagated inwards from the edges by a cooperative process of point-by-point matching^{4,6}, but it seems unlikely that such a mechanism operates under interpolation conditions.

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1. Julesz, B. & Chang, J. J. *Biol. Cybernet.* **22**, 107-120 (1976).
2. Finney, D. J. *Probit Analysis: A Statistical Treatment of the Sigmoid Response Curve* (Cambridge University Press, 1952).
3. Foley, J. M. *Vision Res.* **16**, 1263-1267 (1976).
4. Marr, D. & Poggio, T. *Science* **194**, 283-287 (1976).
5. Marr, D. & Poggio, T. *Proc. R. Soc. B* **204**, 301-328 (1979).
6. Julesz, B. *Foundations of Cyclopean Perception* (University of Chicago Press, 1971).

Changes in the dendritic branching of adult mammalian neurones revealed by repeated imaging *in situ*

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A major obstacle to understanding the mechanism of long-term change in the vertebrate nervous system has been the inability to observe the same nerve cell at different times during the life of an animal. The possibility that changes in neural connectivity underlie the remarkable flexibility of the nervous systems of mammals has therefore not been tested by direct observation. Here, we report studies in which we have visualized the same neurone in the superior cervical ganglion of young adult mice at intervals of up to 33 days. This collection of nerve cells is particularly accessible and therefore well suited to our approach. We find that the dendritic branches of the neurones examined change appreciably over intervals of 2 weeks or more; some branches retract, others elongate and others seem to form *de novo*. The apparent remodelling of these postsynaptic elements implies that the synaptic connections of these cells normally undergo significant rearrangement beyond what is usually considered to be the developmental period.

Sexually mature male mice (8-12 weeks old, 25-35 g, CF1 strain) were anaesthetized with chloral hydrate and mounted on a platform that could be moved in three axes for positioning and focusing. Either the right or the left superior cervical ganglion was exposed through a midline incision, care being taken to preserve the blood supply. The wound was superfused with sterile lactated Ringer's solution (Travenol) and the pool of fluid grounded with a chloride-treated silver wire. The ganglion surface was illuminated at an oblique angle by a plastic light guide (diameter 0.7 mm). Proper adjustment of the angle of illumination caused the neurones on the surface of the ganglion to appear as a mosaic of polygonal cell outlines (Fig. 1a). Individual neurones could be identified as a result of variations in size, shape, neighbour relationships and position with respect to blood vessels. A particular nerve cell was selected for study and 35-mm colour transparencies were taken of the relevant region of the ganglionic surface at a magnification of $\times 35$ - $\times 320$. Following photography, the neurone that had been selected was impaled under direct vision at a magnification of $\times 125$ with a microelectrode filled with a 6% solution of 5(6)-carboxyfluorescein in 0.44 M KOH (pH 7.0; resistance 80-150 M Ω). Resting potentials usually ranged from -40 to -60 mV; all cells had overshooting action potentials, occurring either spontaneously or elicited by current injection through the microelectrode. The illuminator was then turned off and the dye injected iontophoretically by passing hyperpolarizing current for 2 min (3-4 nA d.c.). Subsequent observations of the cell were made on a video monitor with a low-light level video camera (GE model 4TE56 SIT) and a $\times 40$ water-immersion lens with a