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Conditions under which stereopsis and motion perception are blind

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Abstract. We describe modified random-dot stereograms in which the corresponding elements differ from non-corresponding elements in colour, size, and luminance. Despite these visible differences between the elements, depth perception collapses when the spatially integrated luminous flux is similar for the corresponding and non-corresponding elements. Our results suggest that a low-pass spatial filter precedes the mechanism that recognises disparity. A similar phenomenon is observed for the perception of coherent motion in random-dot kinematograms. Our modified stereograms and kinematograms may find other uses when experimenters wish to study the contribution of colour to visual processes and require a method of eliminating edge artifacts.

1 Introduction

So resourceful is the human visual system, and so exquisite is its discrimination, that there is especial interest in its failure under circumstances where one might expect it to succeed. We describe such failures in stereoscopic depth perception and in the perception of coherent motion.

In the classical random-dot stereograms of Julesz, the arrays presented to left and right eyes are constructed from light and dark elements (Julesz 1964). For different subregions of the array, the task of the visual system is to find the binocular disparity that maximises the coincidence of elements of the same luminance. The visual system readily solves this task and the different subregions are perceived at different depths according to their relative disparities.

It is known, however, that depth perception is impaired or abolished when the elements of a random-dot stereogram are of similar luminance and the matching elements are distinguished from non-matching elements only by their chromaticity: some studies have found complete loss of stereopsis under these conditions (Gregory 1977; Lu and Fender 1972) while others have found some residual discrimination (De Weert and Sadza 1983; Jiménez et al 1997). In such equiluminant versions of the traditional random-dot stereogram, the elements are abutting squares of, say, red and green. In determining whether stereopsis is abolished at equiluminance, the experimenter faces the difficulty of eliminating edge artifacts at the boundaries between the two hues—artifacts that may arise from the chromatic aberration of the eye, from misconvergence of the guns of a monitor, or from nonlinearities between the driver and the monitor (Mollon and Baker 1995). If stereopsis survives at equiluminance, there is always the possibility that it is sustained by such artifacts.

In a manoeuvre to sidestep these problems, we were led to a modified stereogram in which each element has its own high-contrast contour that is likely to mask small chromatic artifacts. The individual elements of the stereogram are embedded in a black grid. When this is done, stereopsis reliably collapses at equiluminance. But the most interesting result is found when the red and green elements are of different size,

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as in figure 1. Although both size and colour could now be used by the visual system to solve the correspondence problem, a collapse of stereopsis is still obtained. The collapse, however, no longer occurs when the red and green elements are of equal luminance but rather when they are similar in total luminous flux, that is, in the product of luminance and area for a single element.

The reader may be able to observe our result in the stereo pairs of figure 1, where the upper pair should offer a much stronger depth perception than the lower. Each stereogram consists of 50×50 red or green elements superposed on a black background, and the magnified fragments illustrate how the stereograms are constructed. In the upper panel (a), the red and green cells are close to being equiluminant, but the free-fusing reader should readily recognise a central disc lying in a distinct plane. In the lower panel (b), the lightness of the smaller green cells is so chosen that red and green cells present a similar luminous flux to the eye when luminance is integrated spatially within a cell. So the individual elements here differ in (i) size, (ii) luminance, and (iii) colour; and in principle the visual system could use any one of these cues to identify corresponding elements in left and right eyes, so as to generate a stereoscopic percept. Yet depth perception is weak or absent.

We have performed formal experiments to confirm the phenomenological observations that can be made with stimuli like those of figure 1. Rather than attempting to establish equiluminance in advance for a given subject, we used a performance measure to discover the luminance values of the red and green elements at which stereoscopic discrimination falls to chance in different conditions.

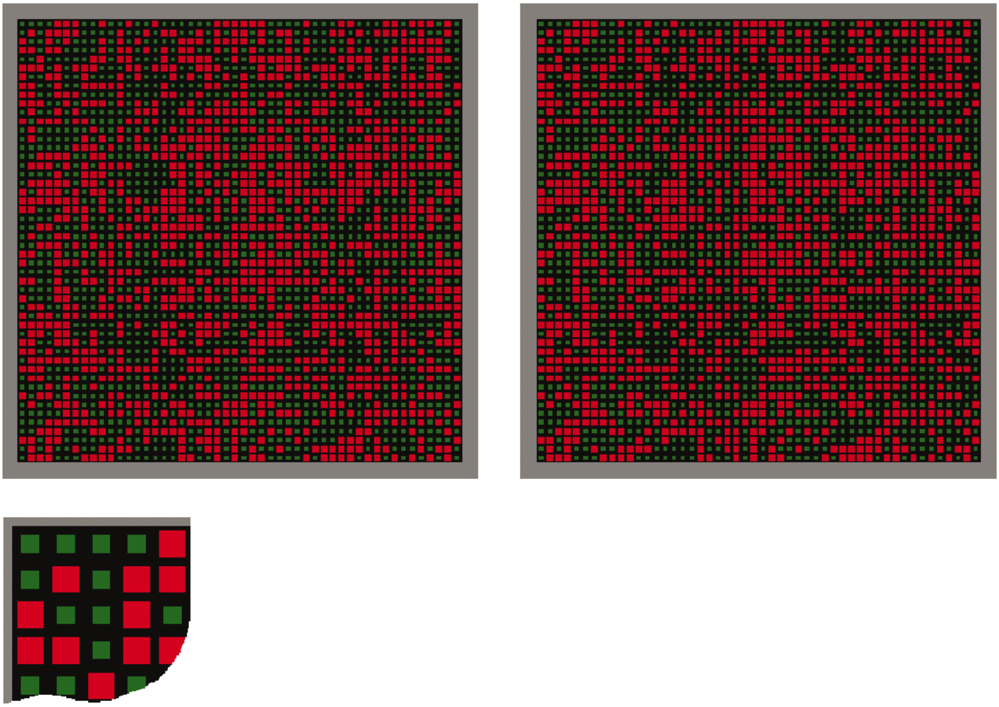
2 Experiment 1

2.1 *Methods*

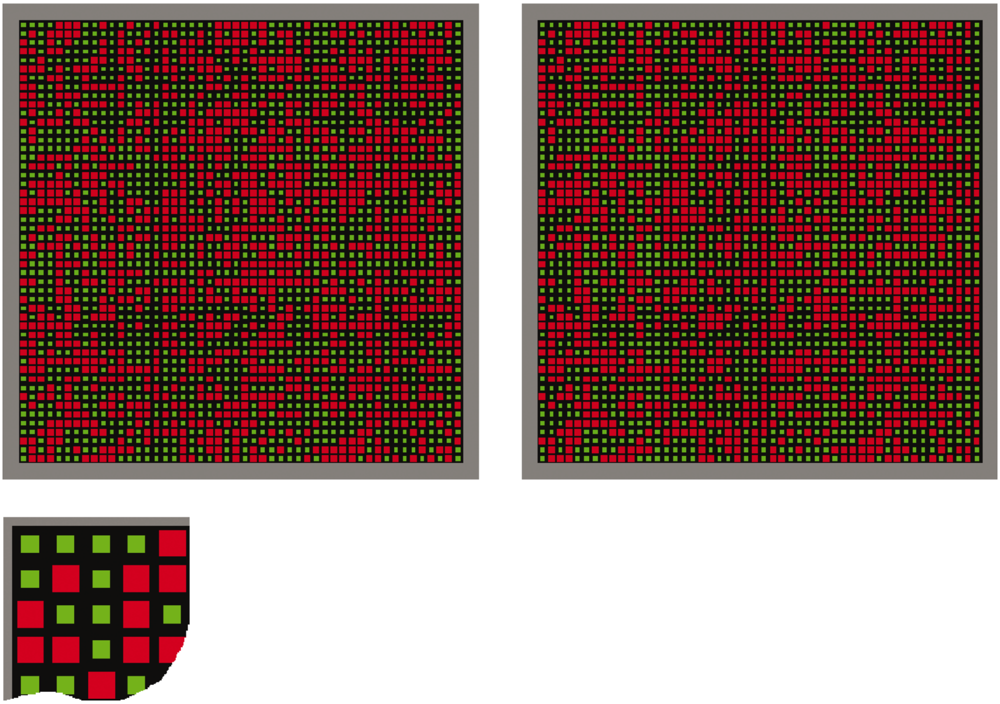
Stereogram pairs were presented on a calibrated graphics monitor (Sony Trinitron monitor GDM 1936) controlled by a Cambridge Research Systems graphics board (VSG/1) mounted in a PC. The left and right images were combined with a mirror stereoscope. The stimulus array subtended 4.14 deg overall. Each stereogram consisted of 50×50 elements embedded in a black matrix as in figure 1. The green elements of the stereogram were fixed at 12 cd m^{-2} but their size could be 3.76 or 2.51 or 1.25 min of arc (equivalent to 6×6, 4×4, or 2×2 pixels). Conversely, the red elements of the stereogram were fixed in size (at 3.76 min of arc) but their luminance was varied. The CIE (1931) chromaticity coordinates of the red and green elements were $x = 0.421$, $y = 0.285$; $x = 0.239$, $y = 0.375$, respectively. These two chromaticities lie on a line that passes through equal-energy white and that holds constant the excitation of the short-wavelength cones. The duration of a single presentation was 500 ms.

The left and right stereograms of a given pair were identical except for a central disc (subtending 2.1 deg), which had a crossed or uncrossed disparity equivalent to one cell of the

Figure 1 (opposite). Stereograms similar to those used in the experiments. The magnified fragments to the left illustrate how the stereograms are constructed. In (a) the red and green elements of the array are of equal luminance but different in size: the red squares correspond to 6×6 pixels on a monitor screen, whereas the green squares correspond to 4×4 pixels. In (b) the red and green elements have the same spatial properties as in (a) but the luminance of the green elements is increased so that the total stimulus flux from the green squares is similar to that from the larger red squares. Observers who can free-fuse the upper pair of stereograms should see a clear disc in depth (lying behind the base plane if cross fusion is used), whereas little or no depth is seen in pair (b). We cannot control exactly the printing process, nor the spectral composition of the illuminant in which the reader is sitting, nor the reader's spectral sensitivity; thus the printed figures (a) and (b) will not correspond perfectly to equal luminance and equal flux, respectively. The interested reader could manipulate the red – green balance by viewing the figures in illuminants of different colour temperature. The original figure is available at http://www.perceptionweb.com/perc0102/kim.html.



(a)



(b)

stimulus matrix. In a two-alternative forced-choice procedure, the subject was asked to report whether the disc-shaped region lay in front of or behind the rest of the array.

Before the main experiments, preliminary trials were made to establish the appropriate luminance range to use for each size of the variable-sized squares. Each of the main experimental runs contained 40 randomly ordered trials, corresponding to 40 different luminance values within the range selected. Within a given run, all other parameters were held constant. In successive runs, the three possible sizes of the variable-size square were tested in order of decreasing size, and this sequence was repeated until 25 runs had been devoted to each size.

The subjects were emmetropic graduate students, one male (JC), one female (SD). Both were normal trichromats with good colour discrimination, as tested by the Nagel anomaloscope and Farnsworth – Munsell 100-hue test. They were paid for their participation.

2.2 *Results: Stereopsis*

Figure 2 shows the relationship between the luminance of the variable (red) elements and the probability of a correct report of the sign of the disparity. Under all conditions in this figure there exists a luminance value of the red elements at which performance falls to chance. However, this value depends very considerably on the size ratio of the red and green elements becoming smaller as the area of the green elements is reduced. The exact positions of the minima are different for the two subjects, and this is not remarkable, since spectral luminous efficiency curves are known to vary for different subjects and do not necessarily coincide with the tabulated values of the standard observer (Kaiser 1988).

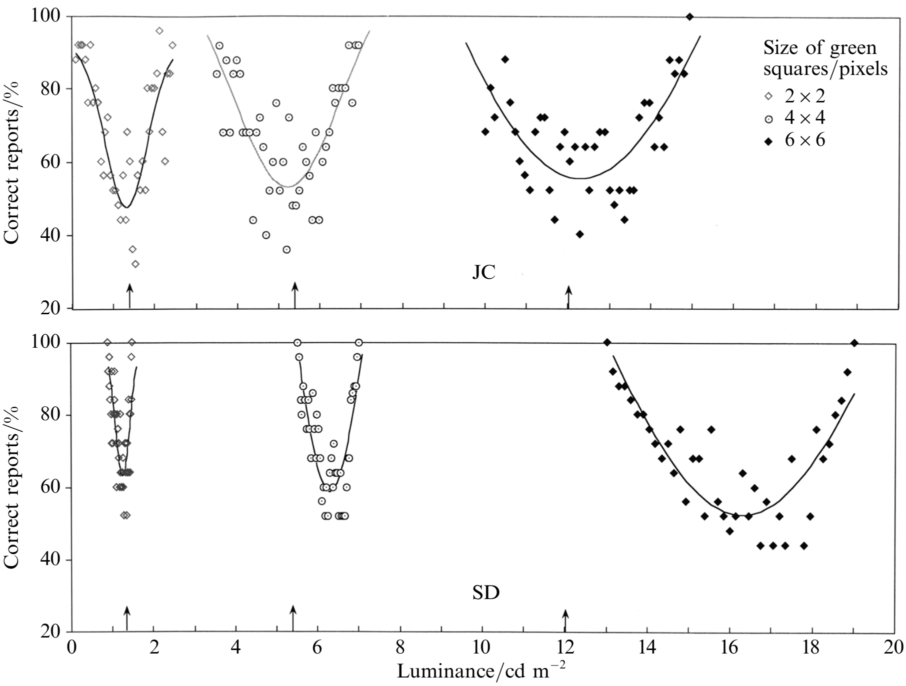


Figure 2. Results of experiments with stereograms in which the green elements were held constant in luminance (12 cd m^{-2}) and the luminance of the red elements was varied in order to establish a pessimum—a region of minimum accuracy. The ordinate represents the percentage of trials on which the subject correctly reported the direction of the depth difference; and the abscissa represents the luminance of the red elements. The three data sets for each subject correspond to green elements of different sizes (2 × 2, 4 × 4, and 6 × 6 pixels). When the green elements are smaller than the red elements, the minimum performance is seen when the luminance of the red elements is reduced and when the total fluxes of red and green elements are *approximately* equal. The vertical arrows indicate the theoretical values for equal flux.

But what is important is that the pessima (the minima of performance) do not lie at the same value for different sizes of the green elements: when the green elements subtend 2.51 min of arc (open circles) or 1.25 min of arc (open diamonds), the pessima are shifted to much lower luminances than the value obtained when the red and green elements are of equal size (solid diamonds). For JC the pessima coincide very closely with those luminances (vertical arrows) that yield equal luminous flux, integrated over the area of the red or green element. For the female observer SD the shift of the pessima is of similar magnitude, although the pessima do not correspond exactly with the values to be expected from integrated luminous flux, calculated in terms of the CIE standard observer. The solid curves fitted to each set of data points are inverted Gaussians: note that the functions become narrower as the pessimum shifts to the left, suggesting that the range of impaired stereopsis is more proportional to the luminous flux rather than to the luminance of the larger elements.

We have obtained very similar results for stereograms consisting of 33×33 elements, where the basic size of the red elements was 6.27 min of arc and the size of the green squares was either 6.27 or 5.01 or 3.76 min of arc. One way to express our results is to say that the channels underlying stereopsis obey Riccó's law of areal summation for stimulus widths up to 6.27 min of arc, whereas the summation areas are much smaller for channels underlying detailed form vision.

Similar phenomena were observed when all the elements of the stereograms were achromatic (CIE 1931 chromaticity coordinates 0.33, 0.33), the black borders being retained: in this case it is clear that stereopsis must collapse when all the elements are of the same size and the same luminance, but when the two subsets of elements were of different sizes, then stereopsis failed when they presented similar fluxes to the eye.

Our results confirm that stereopsis collapses when the elements of a random-dot stereogram differ only in colour (and are approximately constant in luminous flux). In most conditions, we obtained a complete failure of stereopsis despite the fact that we used a forced-choice performance measure and despite the fact that our subjects were highly trained.

The way that the visual system exploits movement parallax is analogous to the way that it exploits binocular parallax (Julesz 1971). In random-dot kinematograms the individual arrays are constructed in the manner of random-dot stereograms, but the two members of a pair are presented successively, and the displacement of a disparate subset of elements gives rise to a perception of coherent motion. When stimuli such as those of figure 1 are presented successively as kinematograms then the same rules hold as for the stereoscopic case: if the red and green elements are of different size, then the perception of motion is more impaired when the red and green elements are of the same luminous flux than when they are of the same luminance. In experiment 2 we present a limited set of measurements obtained with a performance measure.

3 Experiment 2

3.1 *Methods*

Random-dot kinematograms were presented on a calibrated Sony Trinitron graphics monitor (GVM-1400QM) under the control of a Cambridge Research System graphics board (VSG/1). The frame rate of the monitor was 60 Hz. The display was viewed binocularly from a distance of 1.2 m.

The kinematograms were constructed in a similar way to the stereograms of figure 1. Each stimulus consisted of 50×50 elements embedded in a black matrix as in figure 1. The green elements of the array were fixed in luminance at 20 cd m^{-2} but their size could be 3.9 or 2.6 or 1.3 min of arc (equivalent to 6×6, 4×4, or 2×2 pixels). Conversely, the red elements of the stereogram were fixed in size (at 3.9 min of arc) but their luminance was varied.

Two arrays were presented in an alternating sequence. The two arrays were identical except that a square-shaped region in the centre of the array was displaced either vertically or horizontally by a distance equivalent to one cell of the matrix. The axis of displacement was chosen randomly. Each of the two arrays was presented for 6 frames, corresponding to 98.6 ms, with an interstimulus interval of 2 frames, corresponding to 33.2 ms. Each cycle of alternation was repeated 5 times, giving a total presentation time of 1318 ms. The observer's task was to indicate whether the displacement was vertical or horizontal.

The subject was the first author (YK), who is colour normal and myopic; normal spectacle corrections were worn during the measurements. Each stimulus condition was tested once in each of 20 separate runs.

3.2 *Results: Motion*

Figure 3 shows results for random-dot kinematograms. The ordinate shows the percentage of trials on which the subject correctly reported the direction of movement and the abscissa shows the luminance of the red elements, which were fixed in size at 3.9 min of arc. When the red and green elements are of equal size (solid diamonds), the pessimum falls close to equal luminance, confirming previous reports (Cavanagh et al 1985; Ramachandran and Gregory 1978); but when the size of the green elements is reduced, the pessimum is shifted considerably to the left and lies closer to luminance values that would give equal luminous flux.

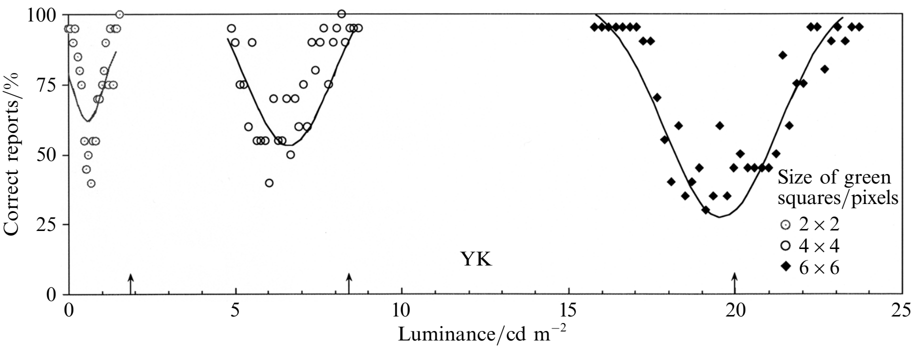


Figure 3. Results of experiments with random-dot kinematograms analogous to the stereograms of figure 1. The ordinate represents the percentage of trials on which the observer correctly reported the direction of movement; and the abscissa represents the luminance of the red elements. The latter were fixed in size (6×6 pixels), whereas the green elements were fixed in luminance (20 cd m^{-2}) and varied in size. The three data sets correspond to green elements of 2×2, 4×4, and 6×6 pixels. When the red and green elements are unequal in size, the minimum performance does not occur at equal luminance but at a value closer to equal flux.

4 General discussion

The results of experiment 1 show that stimuli of sizes up to at least 6.27 min of arc are treated as nearly equivalent by the stereo system, in that the collapse of stereopsis occurs when targets are of similar flux rather than when they are of equal luminance. Yet the variations in size and in luminance are quite visible to the subject. This blindness of stereopsis is an example of the more general principle that information available to one sensory system may not be available to another (Goodale and Humphrey 1998).

The implication of our results is that depth perception in random-dot stereograms depends on a system that is low-pass in spatial-frequency terms. Although stereoscopic resolution for isolated targets lies in the hyperacuity range (Westheimer and McKee 1979) and although thresholds remain under 1 min of arc when such targets are bandpass filtered with a centre frequency of 22 cycles deg^{-1} (Westheimer and McKee 1980), our conclusion is consistent with the observation of Livingstone and Hubel (1987), who constructed stereograms from orthogonal gratings and found that depth could not be seen when the spatial frequency of the gratings exceeded 10 cycles deg^{-1}. Similarly, in masking experiments, Yang and Blake (1991) found that very little noise was required to destroy stereopsis when the target stimulus was filtered with a centre frequency of 12 cycles deg^{-1}, suggesting that high spatial frequencies contribute only weakly to stereopsis.

Experiment 2 reveals a similar limitation in the perception of motion when red–green random-dot kinematograms are constructed by analogy with the stereograms of figure 1. Our result suggests that a low-pass filter precedes the mechanism that detects coherent motion in random-dot kinematograms. Such a hypothesis has been advanced by Morgan who postulated a Laplacian-of-a-Gaussian filter with a standard deviation of 8–16 min of arc, in order to explain the constancy of the spatial limit for movement discrimination (D_{max}) in black-and-white random-dot kinematograms (Morgan 1992). In this, as in other respects, the perception of motion in random-dot kinematograms resembles the perception of depth in random-dot stereograms.

A critical feature of our modified random-dot stereograms and kinematograms is that the individual red and green elements of the array are embedded in a regular black matrix, rather than being apposed as in previous studies. In this respect the present stimuli resemble the very first pseudoisochromatic plates, invented for colour vision testing by Stilling (1877). In Stilling's case, the elements of one colour formed a target figure and the elements of a second colour formed the background. The black matrix serves to mask any residual edge artifacts, arising from the eye's chromatic aberration or from a CRT monitor or, as in Stilling's case, from imperfections of the printing process. This manoeuvre may recommend itself in other situations where the experimenter wishes to isolate the contribution of colour to a visual process.

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