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18 Vision at Equiluminance

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Introduction

In 1927, Susannah Liebmann reported unusual distortions in images viewed at equiluminance. She had hung figures cut out of paper in front of a backdrop and projected one colour of light on the figures and a different colour on the background. When observers adjusted the relative luminance of the figure and ground, they reported a 'critical zone (where) everything flows... glimmers... most everything is soft, jelly-like, colloidal. Often... parts which belong together in the normal figure now have nothing to do with each other. (It is) a world without firm things, without solidarity.' (Liebmann, 1927, pp 308 and 310). Fifty years later, Gregory (1977) using a dual projector (overhead plus opaque projectors) and figures silk-screened on transparencies, again reported intriguing distortions: an image when adjusted to equiluminance 'looked unstable in contrast and 'jazzy'... (and would occasionally) fade, almost as though it were retinally stabilized'.

Given these and other dramatic reports, we tend to think of equiluminous stimuli as blurry, jazzy images that produce only weak impressions of motion and depth and that possibly contribute little to perception other than attractive colours.

On the other hand, later studies suggest that the visual system is, in fact, quite sensitive to chromatic stimuli and able to extract position, motion and depth information in chromatic images as well as in luminance-defined images. To understand the range of opinions concerning the contribution of colour to spatial and temporal aspects of vision we must first decode the term equiluminance. In this chapter, I shall describe the assumptions underlying the concept of equiluminance and review the capacities of the chromatic pathways revealed by equiluminous stimuli and the message this gives us about form and motion processing in the visual system. Finally, I shall describe the advantages and disadvantages of various techniques for producing equiluminous stimuli. This chapter is not a review of colour vision, for which I would recommend several excellent articles (De Valois and De Valois, 1975; Boynton, 1988; Lennie and D'Zmura, 1988; Mollon, 1989; Kulikowski and Walsh, Chapter 16) and books (Boynton, 1979; Hurvich, 1981; Volume 6, this series), but a description of the quality of spatial and temporal vision provided by chromatic images.

Colour: What Is It Good For?

What should we expect from colour in its contribution to spatial and temporal vision? According to Gregory (1977) or Livingstone and Hubel (1987), very little. Gregory (1977) proposed that luminance provided a master map of contours and that qualities such as colour and texture merely filled in the spaces between these luminance defined contours. However, a quick glance at the pseudo-isochromatic Ishihara plates shows that colour alone can certainly define shapes for our visual systems. It does not act only as a 'fill'. The ability to see shapes defined only by colour brings up a simple question. Why should the visual system bother to analyse shape based on colour when luminance provides much more detailed information?

One reason is that a great number of the luminance contours in a natural scene are illumination edges – shadows and highlights. They need to be identified and ignored in order to discover the true object contours and material boundaries. Discontinuities in colour are much more reliable indicators of material boundaries (colour changes at shadow borders are generally subtle). An independent analysis of shape based on colour should therefore be helpful in disambiguating material borders from illumination borders. Moreover, many surfaces are distinguished from their surrounds by both luminance and colour differences. A parallel analysis of contour for colour and luminance information should therefore provide redundant sources of information that should improve contour localization in noisy images.

A second reason for the evolution of shape analysis based on colour is that animals, both prey and predator, develop camouflage to match their mean luminance to that of the background. An evolutionary response is to develop form vision based on colour that defeats the camouflage.

I shall consider in later sections how these advantages of colour-based form vision translate into performance by the visual system.

Pathways and Equiluminance

The notion of equiluminance requires a luminance pathway which responds univariantly to an intensity dimension of coloured stimuli (Hurvich and Jameson, 1957). The luminance pathway in its traditional form (Fig. 18.1) takes its input from the sum of the long- and medium-wavelength-sensitive cones (R and G cones, respectively) although some psychophysical studies indicate that the short-wavelength-sensitive cones (B cones) may also contribute to some extent (Drum, 1983; Lee and Stromeyer, 1989; Stockman *et al.*, 1991). The chromatic signals arise from the differences between cone signals: R-G and B-(R + G) for the red/green and blue/yellow opponent-colour pathways, respectively. An equiluminous stimulus is one that varies in colour but not in luminance. These stimuli are used by psychophysicists to provide information to the chromatic pathway but not the luminance pathway and so to test the capacities of the chromatic pathways in isolation.

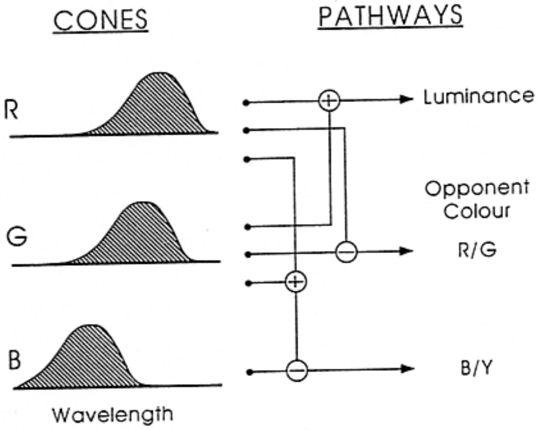

Fig. 18.1 *The three different cone classes sensitive to long, medium and short wavelengths (R, G, and B cones, respectively) have adsorption spectra of similar shape that differ in the wavelength of peak sensitivity. The R and G cone responses combine additively to form the luminance pathway and subtractively to form the red/green opponent-colour pathway. The blue/yellow opponent-colour pathway is formed from the difference between the B cone response and the sum of the R and G cone responses.*

The psychophysical distinctions between luminance and chrominance processing are based principally on spatial and temporal resolution. The luminance pathway has high spatial and temporal resolution while the chromatic pathways do not. This difference is the basis of two of the standard measurements of luminance: minimum flicker photometry which is performed at high temporal frequencies and minimum border photometry which relies on high spatial frequencies. Luminance, as measured by a photometer in cd m^{-2}, is meant to predict the response of the luminance pathway as evaluated principally by minimum flicker and averaged over a large number of observers. Equal photometric luminance, however, does not guarantee equiluminance, the uniform response of the luminance pathway, in a given individual (Kaiser, 1988). The relative luminance of two colours that are equiluminous varies from individual to individual, varies across the retina, and varies also as a function of spatial and temporal frequency (Cavanagh *et al.*, 1987a).

The notion of equiluminance also presumes that there is only one luminance pathway and that it is characterized by a single null: one relative luminance between any two colours for which there is no response of the luminance pathway. In truth, however, there may be many luminance pathways. Image information from separate spatial frequency bands passes through separate units in the visual system – each of these could be considered a separate luminance pathway (low-pass, high-pass, etc.) with, potentially, a different equiluminance point. Given that multiple pathways may be carrying luminance information each potentially with different equiluminance points, it is all the more remarkable that so many dramatic losses in performance occur within a fairly restricted range of luminance values.

There have been many attempts to link the luminance and chromatic pathways identified psychophysically to the magnocellular and parvocellular streams (Livingstone and Hubel, 1987; Maunsell and Newsome, 1987; DeYoe and van Essen, 1988; Zeki and Shipp, 1988) of the primate visual system. The units in the magnocellular stream have little colour sensitivity and respond best to low spatial and high temporal frequencies whereas those in the parvocellular stream generally have colour-opponent responses and prefer high spatial and low temporal frequencies (see Schiller *et al.*, 1990; Shapley, 1990, for reviews). However, there is no simple relationship between these properties and those of the luminance and chromatic pathways. For example, it has been argued (DeValois and DeValois 1975; Ingling and Martinez-Uriegas, 1985; Schiller *et al.*, 1990) that both magnocellular and parvocellular streams are involved in carrying luminance information: The magnocellular stream is principally non-opponent but the parvocellular, although carrying colour-opponent information for low spatial and low temporal frequencies, also carries non-opponent (luminance) information at high spatial and temporal frequencies. Moreover, units in the magnocellular stream exhibit residual, often frequency-doubled, responses to chromatic modulation (Lee *et al.*, 1988; Logothetis *et al.*, 1989; Schiller and Colby, 1983) and clear colour-opponency for large stimuli (Type IV units, Wiesel and Hubel, 1966). In summary, no physiologically distinct structures have yet been identified whose properties correspond in a straightforward way to those of the luminance and chromatic pathways (see for example, Lennie *et al.*, 1990).

Capacities

Focus and Eye Movements

Accommodation

Wolfe and Owens (1981) report that observers cannot focus on equiluminous contours. However, this loss is unlike the others which will be considered later in that the loss is inherent in the optics of the eye – the accommodation information available in the chromatic image is already degraded on the retina due to chromatic aberration.

In order to adjust the focus of the lens, the accommodation system appears to adopt the strategy of maximizing the luminance contrast of sharp borders (high spatial frequencies). Optimal focus could also be based on maximizing chromatic contrast but this is less effective due to chromatic aberration: the optimal focus is different for different colours and so chromatic contrast has a rather broad maximum as a function of accommodation whereas luminance contrast has a much sharper maximum. In choosing to monitor luminance contrast in order to set optimal focus, the accommodation system is faced with a problem for chromatic borders: when equiluminous colour borders are in optimal focus, their luminance contrast is zero. Because of chromatic aberration, however, the accommodation system can create a luminance contrast at an equiluminous border by bringing one of the two colours into focus and slightly blurring the other. This produces a luminance transient at the border that satisfies the accommodation system but not the experimenter. Moreover, the accommodation set in this manner for the chromatic border would be far from optimal for a luminance border at the same viewing distance. The hunting of the accommodation system for optimal luminance contrast in a chromatic image may be part of the discomfort or jazziness produced by equiluminous colours.

Optokinetic Nystagmus

Logothetis and Charles (1988) showed that the optokinetic nystagmus (OKN) produced by drifting equiluminous stimuli was unchanged from that for luminance stimuli. There was no loss in the gain (ratio of eye movement speed to stimulus speed) at any relative contrast between the red and green of their stimulus. Whatever visual representations are monitored to drive OKN, they must respond to chromatic borders as well as to luminance borders.

Visibility

Spatial Acuity

Kelly (1983) has reported contrast sensitivity functions for chromatic and luminance stimuli. These revealed the typical low-pass pattern for equiluminous red/green stimuli. Sensitivity was essentially constant from very low spatial frequencies out to about $0.5\,\mathrm{c\,deg^{-1}}$ and then dropped off rapidly. On the other hand, contrast sensitivity for luminance stimuli had an inverted U-shape with a maximum between 3 and $6\,\mathrm{c\,deg^{-1}}$, and decreasing at lower and higher spatial frequencies. The low frequency roll-off for the luminance response is generally attributed to lateral inhibition and the absence of this roll-off for chromatic functions is taken as evidence for a lack of lateral inhibition in the chromatic pathways.

Mullen (1985) has estimated that the upper limit of visibility for red/green stimuli is about $12\,\mathrm{c\,deg^{-1}}$, whereas that for luminance stimuli is at least $60\,\mathrm{c\,deg^{-1}}$ (Campbell and Gubisch, 1966). Uusvaara and Rovamo (1988) report that the upper limit for tritanopic stimuli (chromatic stimuli differentially stimulating only B cones) is only 3–$4\,\mathrm{c\,deg^{-1}}$. Other studies (Cavonius and Estévez, 1975), including tests of B-cone monochromats (Green, 1972), reveal a somewhat higher upper limit. This low resolution for tritanopic stimuli is also involved in the very weak borders produced by tritanopic colour pairs (Boynton, 1978) to the extent that the border may fade to invisibility or 'melt'.

The poor response to high spatial frequencies (or even to the middle range for tritanopic stimuli) is one of the defining features of the chromatic pathways. This lack of resolution may be the source of the performance losses in many experiments at equiluminance.

Localization

Two studies have indicated that position information may be poorly coded for equiluminous borders. Morgan and Aiba (1985) reported that vernier acuity for equiluminous stimuli is only half as precise as it is for luminance stimuli. These authors used fine lines, however, and the loss of precision may have been a result of the blurring of the test lines at equiluminance. Troscianko and Harris (1988) found that phase discrimination threshold at equiluminance was worse than in any condition involving luminance. Based on these data, they suggested that there is significant positional uncertainty in the neural representation of equiluminous stimuli. However, poor phase discrimination performance implies that observers have less sensitivity to the shapes of chromatic profiles than to those of luminance profiles. It does not necessarily imply a poor representation of position information at equiluminance.

In fact, when observers were tested in an alignment task with blurred lines (Gaussian profile) of equal blur for luminance and chromatic stimuli, the precision of alignment was the same for luminance and chromatic stimuli (Krauskopf and Farrell, 1991). This indicates that when stimuli within the resolution limits for the chromatic pathways are used, the positional information for luminance and chromatic information is comparable.

Do Luminance Borders Capture Colour Borders?

On the other hand, luminance contours do seem to dominate colour contours in determining the motion or depth of objects when both are present. Ramachandran (1987) has demonstrated that moving luminance contours appear to capture static equiluminous colour contours so that they appear to move as well. Similarly, a transparent texture defined by luminance can capture an equiluminous contour lying on a different depth plane so that it appears to lie at the same depth as the texture (Watanabe and Cavanagh, 1990). It remains to be determined whether luminance contours always dominate colour contours when there is a conflict between them in motion or depth. It may be just the contour with higher effective contrast that captures the other.

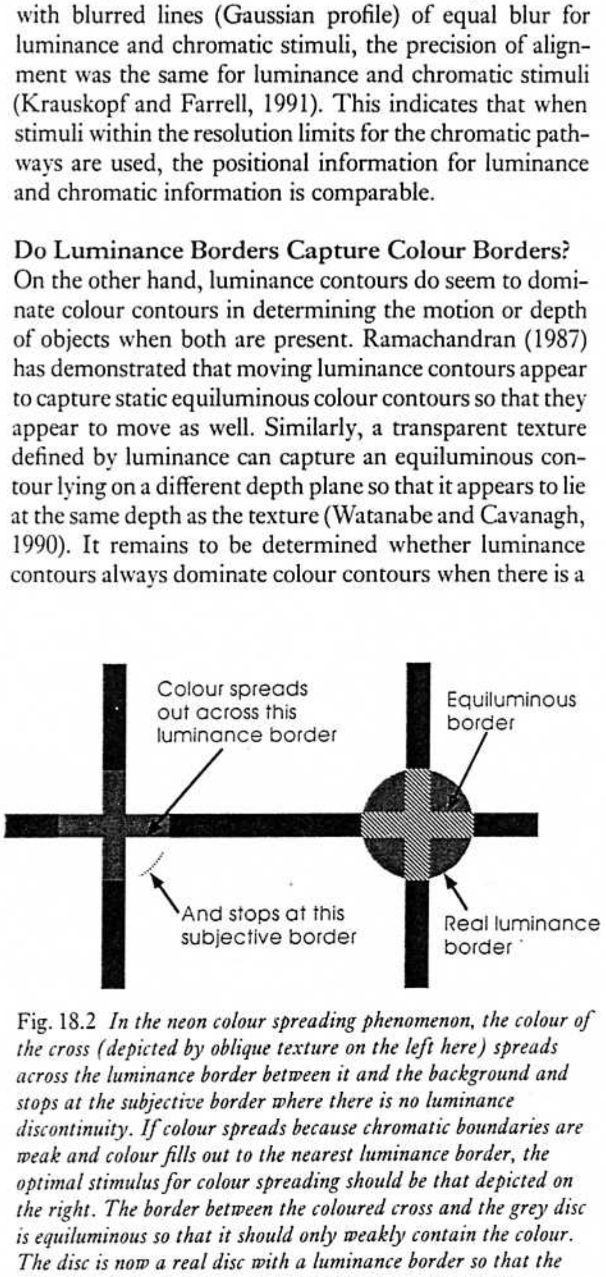

Fig. 18.2 *In the neon colour spreading phenomenon, the colour of the cross (depicted by oblique texture on the left here) spreads across the luminance border between it and the background and stops at the subjective border where there is no luminance discontinuity. If colour spreads because chromatic boundaries are weak and colour fills out to the nearest luminance border, the optimal stimulus for colour spreading should be that depicted on the right. The border between the coloured cross and the grey disc is equiluminous so that it should only weakly contain the colour. The disc is now a real disc with a luminance border so that the colour should stop its spread at this border. In the actual stimulus, however, no colour spreading was noted suggesting that the neon colour phenomenon is not a result of weak localization of chromatic borders but more likely related to inferences of transparency. (From Nakayama* et al., *1990.)*

Neon spreading is a similar phenomenon in the realm of spatial position (van Tuijl, 1975). In the stimulus, coloured lines create a subjective figure and the colour 'leaks' out of the lines to fill the entire subjective surface. At first glance, this result supports Gregory's (1977) conjecture of a master map where luminance defines the contours while colour and texture fill out to the luminance contour in a sort of border locking. Grossberg and Mingolla (1985) also use this phenomenon to build their model of boundary contour system and a feature contour system, similar in spirit to that of Gregory. The phenomenon does not really fit with the theory, however. In particular, colour is required to leak across a luminance border (the coloured cross is darker than the surrounding surface, see Fig. 18.2), and out to a subjective contour where there is, in fact, no luminance border at all. I constructed a version of the figure which corresponded much more closely to the ideal stimulus for colour spreading in Gregory's and Grossberg and Mingolla's models: an equiluminous border between the coloured cross and its surrounding disc, and a real luminance border in the same disc shape as the subjective figure (Fig. 18.2). No colour spreading was observed. This phenomenon may be more related to the inferences of 3D surfaces and transparency that accompany the percept (Nakayama *et al.*, 1990) than to the dominance of luminance over colour in determining border location.

Contrast Range

One aspect of chromatic images that has been little studied is the available contrast range. We can think of this range as the number of just noticeable contrast increments between the threshold of visibility and the maximum contrast obtainable. Brindley (1953) has reported that the contrast range for tritanopic colours (differently stimulating only the B-cones) is extremely compressed. We have informally verified that images appear to have virtually only two levels with little gradation between them in tritanopic displays. Modulation along the red/green colour direction appears to produce a wider range of contrast sensations although this has not been measured explicitly. That the range is still limited compared with luminance gradations can be seen by comparing luminance sine wave gratings with red/green sine wave gratings. A smooth range of luminances can be seen between the light peak and dark trough of a luminance grating. However, unless the spatial frequency is very low, a red/green sine wave grating appears to be principally red and green with little evidence of the intermediate colours of orange, yellow, and lime that are present in the stimulus.

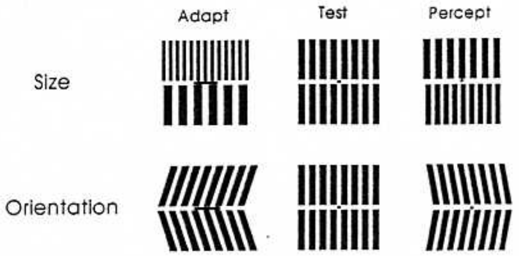

Fig. 18.3 *The possibility that size and orientation are used to code shape for chromatic images can be established by testing for size- and orientation-specific after-effects for chromatic gratings.*

Flicker

Temporal resolution for chromatic stimuli is limited compared with that for luminance stimuli in much the same way that spatial resolution is. Thresholds for detecting chromatic flicker show a low-pass characteristic with little or no response beyond about 15 Hz for red/green flicker (Kelly, 1983). The response to luminance flicker peaks at about 8 Hz, rolling off above and below that value (de Lange, 1958; Kelly, 1983). It extends to 50 or 60 Hz.

2D Shape

How does the visual system encode the shape of stimuli defined by colour? Psychophysical techniques (Fig. 18.3) such as size (Blakemore and Sutton, 1969) and tilt after-effects (Campbell and Maffei, 1971) and simultaneous induction paradigms (Georgeson, 1973; Klein *et al.*, 1974) have been used to infer the existence of size and orientation coding dimensions in the luminance domain and the same procedures can be applied to stimuli defined by colour.

Independent analyses of size and information for colour and luminance have been suggested by findings of simultaneous and opposite size after-effects for colour and luminance stimuli (Favreau and Cavanagh, 1981). That is, not only can size after-effects be induced for chromatic stimuli, but these effects can coexist with size after-effects in the opposite direction that are specific to luminance stimuli. The simultaneous induction of opposing after-effects for colour and luminance has also been demonstrated for the tilt after-effect (Flanagan *et al.*, 1990) suggesting the independent analyses of orientation for colour and luminance. In both of these experiments, an after-effect seen with chromatic stimuli could not be mediated by any residual luminance in the chromatic stimuli, since any after-effect produced by this residual luminance would be overwhelmed by the after-effect in the opposite direction produced by the actual luminance stimuli.

The finding of orientation after-effects for chromatic stimuli is in agreement with threshold measures reported by Bradley *et al.* (1988). Following adaptation to equiluminous coloured gratings, they recorded an elevation in threshold contrast for detecting equiluminous gratings that was selective for orientation. The threshold elevation was most evident for equiluminous coloured gratings and less so for luminance gratings. In addition, orientational anisotropy has been reported for the detection thresholds of chromatic gratings (Murasugi and Cavanagh, 1988). This result also implies that the orientation of chromatic stimuli must be represented explicitly in the visual system.

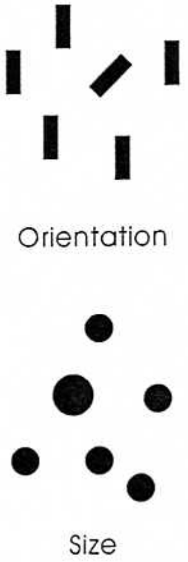

Fig. 18.4 *Stimuli for a visual search task (Cavanagh* et al., *1990). Response times to indicate the presence or absence of a target among distractors (oblique among vertical bars on top or large among small discs below) are recorded and the slope of the response time as a function of the number of distractors is used to classify the search process as parallel or serial. If the slope is very shallow, the search is considered parallel and the feature distinguishing the target from the distractors is considered a primitive feature. In the experiment, these stimuli were presented defined either by luminance (e.g. large and small light discs on a dark background) or by equiluminous colour (e.g. large and small red discs on a green background).*

These findings indicate that similar shape analysis occurs independently for colour and luminance, demonstrating a functional independence between these two attributes that corresponds to the physiological independence suggested by the clinical data of cortical colour blindness (Damasio *et al.*, 1980).

Finally, in collaboration with Anne Treisman and Martin Arguin, I have tested a visual search paradigm studied by Treisman and Gelade (1980) and Julesz (1981) to determine whether size and orientation are privileged features for stimuli defined by, among other attributes, luminance, and colour (Cavanagh *et al.*, 1990). A feature is assumed to be a basic coding dimension if it can be detected in parallel in a field of distractors, that is, if the time required to detect it is independent of the number of distractors. Stimuli like those in Fig. 18.4 were presented with the bars (orientation task) or discs (size task) defined by each attribute in turn. Reaction time to detect the presence of targets was independent of the number of distractors for all stimulus types in the orientation task. For the size task, reaction times were also unaffected by the number of distractors for stimuli defined by luminance or colour. These data again suggest that size and orientation coding are available for stimuli defined by equiluminous colours.

Stereo

Initial studies by Lu and Fender (1972), Gregory (1977, 1979) and others demonstrated that depth in random stereograms was lost at equiluminance even though depth was not lost for figural stereograms. However, de Weert and Sadza (1983) showed that observers actually could judge depth in equiluminous random-dot stereograms even though the subjective impression was very weak. de Weert and I have made some preliminary measurements showing that the depth perceived in a stereogram decreased as the colours approached equiluminance in much the same way that the apparent speed of drifting coloured gratings decreased at equiluminance. Grinberg and Williams (1985) showed that depth could be seen in random-dot sterograms that only stimulated the blue-sensitive cones. Since these stimuli primarily stimulate the blue/yellow opponent-colour pathway, they concluded that colour information did contribute to stereopsis.

More recently, van Sickle and Geisler (1989) and Poeppel and Logothetis (1990) have reported that equiluminous random-dot stereograms provide a robust perception of depth. Their stimuli were blurred in the display to reduce the effects of chromatic aberration. Although depth can be seen, it may appear to be smaller in magnitude than when the same stimulus is presented with luminance contrast. In addition, the definition of the border surrounding the shape in depth may be degraded. Jordan *et al.* (1990) tested the relative contributions of chromatic and luminance information to depth perception using an ambiguous depth display (the wallpaper illusion). They were able to show that chromatic information was used at least as efficiently as luminance information in generating impressions of depth from disparity in these displays.

Motion

Anstis (1970) and Ramachandran and Gregory (1978) have claimed that coloured stimuli, in particular, equiluminous kinematograms, do not produce impressions of motion. However, an attempt to replicate these findings Cavanagh *et al.* (1985) found that motion was visible for equiluminous kinematograms although over a more restricted range of displacements and alternation rates than for luminance-defined stimuli.

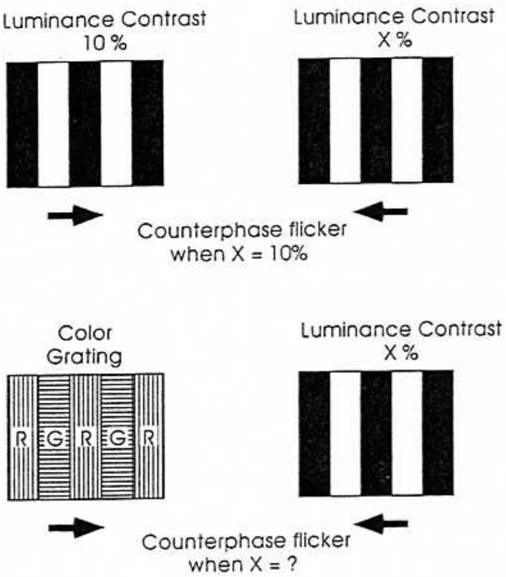

Fig. 18.5 *Two superimposed luminance gratings (shown separately here but superimposed in the display (Cavanagh and Anstis, 1986)) moving in opposite directions produce counterphase flicker when they have equal contrasts (as well as equal spatial and temporal frequencies). When they have unequal contrasts, motion is seen in the direction of the grating with the higher contrast. Adjusting the contrast of one grating to null the motion therefore measures the contrast of the other grating (the contrasts are equal at the motion null). The same technique can be used to measure the equivalent contrast of an equiluminous colour grating. The contrast of a luminance grating necessary to null the motion of the colour grating is taken as the 'equivalent' luminance contrast of the colour grating.*

Drifting equiluminous sinewave gratings also produce a perception of motion (Cavanagh *et al.*, 1984b) but the stimuli appear to be significantly slowed and occasionally stopped when compared with stimuli having luminance contrast. Observers were presented with a drifting colour grating in the top half of the field and a comparison luminance grating in the bottom half. They adjusted the speed of the luminance grating until it appeared to match that of the colour grating. When the relative luminance of the two colours approached equality, the apparent speed decreased to 40–60% of the actual speed. If the stimuli were moving quite slowly (less than 0.5° of visual angle per second), they could even appear to stop moving at equiluminance. The coloured bars could be seen clearly and although it was apparent that the bars occasionally changed position this produced no subjective impression of motion. For any stimulus that could produce this stopped-motion phenomenon, the perception of motion could be reinstated by increasing the speed of the stimulus. The contribution of colour to motion perception may therefore be weaker than its input to pattern perception, so that a particular stimulus can be above its pattern threshold and be seen clearly as coloured bars, but below its motion threshold so that the bars did not appear to move.

These results show that motion can be seen for coloured stimuli, and experiments based on motion after-effects (Cavanagh and Favreau, 1985; Derrington and Badcock, 1985; Mullen and Baker, 1985) show that this is not due to an independent motion analysis for coloured stimuli but to a common motion analysis to which both colour and luminance contribute. Following adaptation to drifting luminance gratings, motion after-effects could be seen on equiluminous coloured tests, and vice versa, implying a single, common site for motion adaptation. In addition, following adaptation to a luminance grating, the motion after-effect seen on a coloured test could be nulled by moving the coloured test in the opposite direction (Cavanagh and Favreau, 1985), an interaction that requires a common motion pathway accessed by both colour and luminance information (see Gorea and Pappathomas, 1989, for a different view). If colour and luminance stimulated independent motion detectors, we would expect that they would not null each other but appear as transparent stimuli sliding over each other as do luminance gratings when they differ sufficiently in spatial frequency (Adelson and Movshon, 1982).

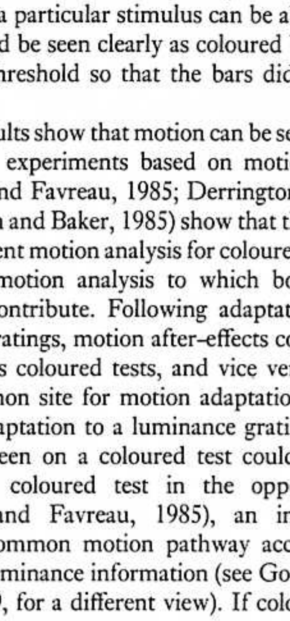

Fig. 18.6 *The 3D structure of a large, chunky object (a) can be recovered from its 2D projection as it rotates even at equiluminance (red object on an equiluminous green field (Cavanagh and Ramachandran, 1988)). The 3D structure of a sphere whose surface is sprinkled with fine dots (b) cannot be recovered from its 2D projection as it rotates at equiluminance (Livingstone and Hubel, 1987).*

This nulling of motion between colour and luminance gratings has been used to measure the strength of the contribution of coloured stimuli to this common motion pathway (Cavanagh and Anstis, 1991). The contrast of an unknown grating can be measured by varying the contrast of an otherwise identical grating moving in the opposite direction (Fig. 18.5). The direction of perceived motion of the combined gratings is determined by the grating with the higher contrast. When the two gratings have equal contrast, a motion null – counterphase flicker – is obtained. Observers adjusted the contrast of a luminance grating until it just nulled the motion of a colour grating moving in the opposite direction. This contrast setting was taken as the 'equivalent luminance contrast' of the colour grating. The equivalent contrast for colour stimuli was, at best, about 12%, one eighth the maximum contrast possible for luminance stimuli. The equivalent luminance contrast for tritanopic stimuli (green/purple) was about 4%.

Motion in Depth

Drifting equiluminous gratings have also been used to test for stereomotion thresholds (Tyler and Cavanagh, 1991). Vertical gratings were drifted in opposite directions in the two eyes and observers reported a strong impression of motion in depth even at equiluminance. The motion thresholds as a function of temporal frequency showed the low-pass pattern typical of chromatic stimuli. Luminance stimuli show a phenomenon known as binocular motion suppression (Tyler, 1971) in that the threshold for binocular motion in depth is higher than that for monocular motion. In other words, if an observer sees no motion when viewing the stimulus binocularly, the motion can be rendered visible just by closing one eye. This phenomenon did not occur for chromatic stimuli indicating that the interaction of motion and binocular factors is different for chromatic and luminance information (Tyler and Cavanagh, 1991).

Livingstone and Hubel (1987) reported that the kinetic depth effect was lost at equiluminance. They used the two-dimensional (2D) projection of dots on the surface of a rotating sphere (Fig. 18.4). When luminance contrast was present, the dots produced a strong impression of a 3D sphere. At equiluminance, however, the sphere collapsed and the dots appeared to be swimming back and forth on a flat plane. One problem with their display is that the dots were small so that at equiluminance it was difficult to see the motion of the dots except near the fovea. Dots in the periphery produced only a flickering porridge of ill-defined texture which was sufficiently unlike a rigid 3D object to destroy the impression of the 3D sphere. When the same experiment was attempted with rotating objects whose motion was visible in the periphery at equiluminance (thick, bent rods and cylinders with large random stripes, see Fig. 18.6), recovery of depth from motion was as strong as for luminance-defined stimuli (Cavanagh and Ramachandran, 1988).

Parallax

Livingstone and Hubel (1987) also reported that depth from parallax was lost at equiluminance. However, a more recent study (Rivest *et al.*, 1990) using equiluminous sine wave gratings, found that parallax produced reduced but reliable impressions of depth at equiluminance. The reduction in depth was principally accounted for by the reduced apparent velocity of the equiluminous stimuli.

Texture

McIlhagga *et al.* (1990) recently showed that the perception and segregation of texture was possible for equiluminous stimuli. The authors were able to show that the strength of the segregation was determined solely by the visibility of the texture elements whether they were defined by luminance or by colour. They concluded that there were no inherent differences between colour and luminance in their ability to produce textures once visibility was taken into account.

Do Visible 2D Forms Support 3D Inferences?

We know that colour alone can produce visible 2D shapes. Do these shapes support 3D inferences through pictorial cues? Tests can be made with stimuli such as the Necker cube, perspective drawings, geometrical illusions, shadows and subjective contours with each figure presented in equiluminous colour. To make meaningful tests, it is necessary to use highly visible figures with no fine detail otherwise the inability to perform a particular task may be due simply to the reduced resolution or contrast inherent in a particular representation.

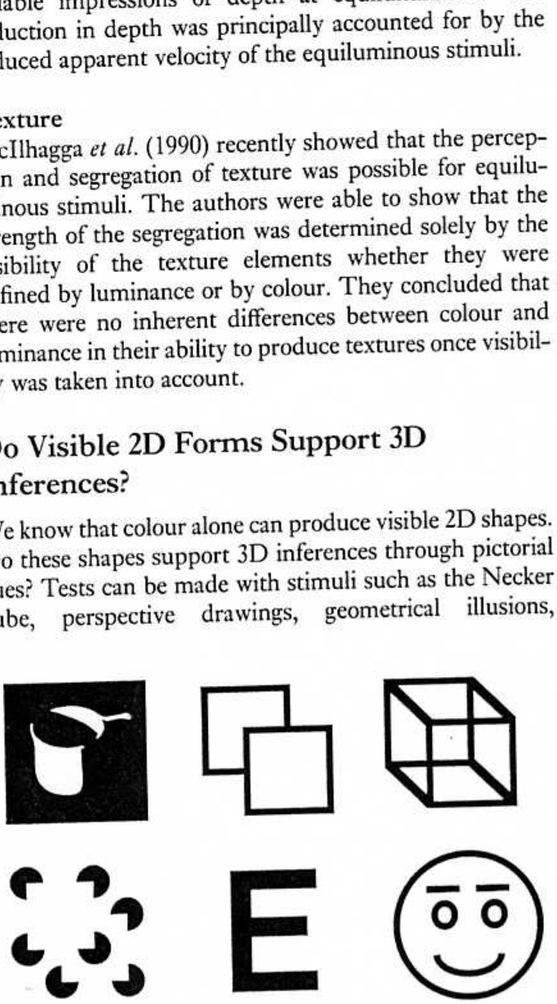

Fig. 18.7 *The four stimuli on the right have explicit contours and their 2D (for the letter E) and 3D (for the overlapping squares, the cube, and the face) shapes can be recovered at equiluminance (Cavanagh, 1987). The 3D shapes of stimuli with implicit contours, however, (shadows and subjective contours) cannot be recovered at equiluminance (Cavanagh and Leclerc, 1989).*

Explicit Contours: Line Drawings, Perspective, Vertices

Information signalled by equiluminous stimuli having explicit contours, e.g. T-junctions indicating occlusion (Fig. 18.7), was effective in generating impressions of 3D shape (Cavanagh, 1987). Simple, two-dimensional letter shapes could be easily identified and three-dimensional objects defined by complete contours in line drawings involving occlusion and perspective were interpreted in the same fashion whether represented by luminance or colour. Shape information involving explicit object contours therefore appears to be represented equally well in luminance and in colour. There was no indication that luminance information had any privileged role to play in these images other than the extra resolution it affords. The demonstrations of Livingstone and Hubel (1987) of loss of 3D structure in line drawings may be attributable to the fine detail of their stimuli so that it was the stimulus detail, not the analysis of pictorial depth cues, that was lost at equiluminance.

Implicit Contours: Shape from Shadows, Subjective Contours

The results for stimuli involving implicit contours are strikingly different. Neither shape from shadows (Cavanagh and Leclerc, 1989) nor subjective contours could be seen at equiluminance (Brussell *et al.*, 1977; Cavanagh, 1987; Cavanagh *et al.*, 1987b; Ejima and Takahashi 1988, Fig. 12; although Gregory, 1977, reported some residual, ill-defined percept). In both these cases, object contours are missing in the image either because they are hidden in shadows or because the surface and the background have the same reflectance and, in both cases, a luminance difference was necessary to recover the object's shape (Fig. 18.7). If the parts of the stimuli were presented without a luminance difference, they were interpreted as separate, unconnected islands of colour. If a luminance difference was then introduced, the overall global organization of the stimulus would become visible. Thus the luminance pathway is essential for the perception shadows and subjective contours.

It might seem self-evident that shadows would require luminance information to be properly interpreted: a real shadow is always darker than the adjacent non-shaded region. Shadow analysis may therefore be part of the specialized luminance analysis just as seeing colours is part of the specialized colour analysis. This is not a convincing argument, however, since the inference of depth from shadows must be based on their shape (necessarily in binary images such as Fig. 18.7), not on their darkness. Rainbows can be identified in black and white images because of their shape but depth from shadows is not perceived in images defined only by colour even though all the essential shape information is there. Moreover, it seems unlikely that an early level of the visual system such as the luminance pathway would be independently capable of the depth and surface inferences involved in interpreting shadows. It is reasonable to assume that higher level analyses are participating in these inferences but perhaps these analyses are based on only luminance information. By ignoring shape information in other pathways, the visual system would give up opportunities to reject areas as shadows because of impossible colours. Observers, in fact, saw depth in shadow images having appropriate luminance patterns even when they violated the colour constraints of natural shadows (Cavanagh and Leclerc, 1989).

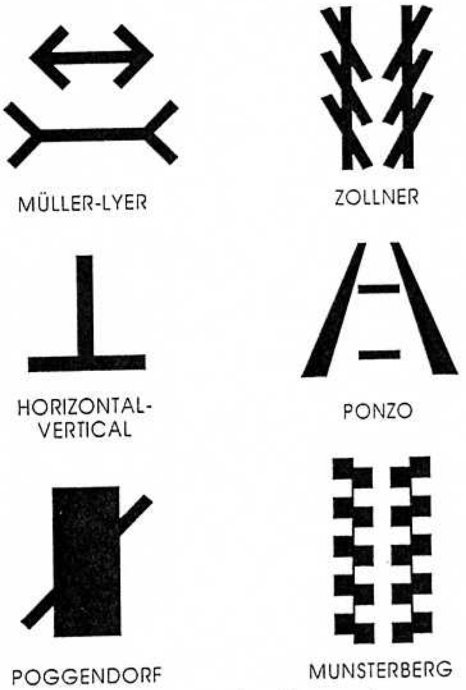

Fig. 18.8 *A number of illusions have been tested at equiluminance. Lehmann (1904) and Liebmann (1927) reported that the Müller-Lyer, Zollner, Munsterberg and Poggendorf illusions were lost at equiluminance although Liebmann claimed that this was due to a loss in the visibility of the stimuli. Gregory (1977) reported that the Müller-Lyer, Ponzo and Zollner illusions were unaffected at equiluminance whereas the Munsterberg (Café Wall) illusion was lost. Livingstone and Hubel (1987) reported that the Zollner illusion was lost at equiluminance although this loss might have been due to the fine lines used to present the stimuli. I have found that the Zollner, horizontal/vertical, Ponzo and Poggendorf illusions are preserved in large illusion figures at equiluminance (Cavanagh, 1986; 1989).*

Luminance may be a natural aspect of shadows, but this is not the case with figures producing subjective contours. Theories of subjective contours are generally based on high-level inferences of occluding surfaces. Gregory (1972), Kanizsa (1979) and Rock and Anson (1979) all suggest that the occluding surface is hypothesized to simplify the interpretation of the image. Thus, in Fig. 18.7, it is easier to see eight circular discs covered by two square, opaque sheets (one disc completely covered) than seven, irregular, three-quarter pie shapes. These cognitive explanations are based entirely on stimulus shape and therefore should be unaffected by the manner in which the shapes are presented. On the contrary, subjective contours were only clearly visible when there was a luminance difference between the regions defining the shapes (Brussell *et al.*, 1977; Gregory, 1977; Cavanagh *et al.*, 1987b; Ejima and Takahashi, 1988, Fig. 12).

Illusions

The earliest experiments with equiluminous stimuli were tests of illusions conducted by Lehmann in 1904 and then repeated by Liebmann in 1927. The central question in these experiments was whether geometrical illusions such as the Poggendorf, Zollner, Munsterberg and Müller-Lyer illusions (Fig. 18.8) were due to irradiation. Irradiation refers to the increase in the apparent size of brighter surfaces and it was thought that this would produce the distortions seen in several illusions. An obvious test for this hypothesis was to use equiluminous stimuli where irradiation could not play a role since both surfaces would be equally bright.

Lehmann (1904) therefore displayed the illusion stimuli in his Chromascope and had subjects adjust the relative luminance of figure and ground. The subjects reported that at a particular setting, the illusions were much reduced, the apparently skewed lines of the Zollner illusion, for example, looked parallel. He concluded that irradiation indeed accounted for these illusions.

Liebmann (1927) repeated these experiments using cutout figures of the illusion stimuli hung in front of a backdrop. The two surfaces were obliquely illuminated by separate projectors whose brightness could be independently controlled. She replicated Lehmann's findings but recorded the observers' reports in greater detail. She noted in particular that the illusion stimuli became very fuzzy and lost much of their detail at equiluminance (or the critical zone, as she called it) to the extent that they were no longer legitimate stimuli for observation of the illusions. She attributed the loss of the illusion strength not to the reduction of the irradiation effect but to the loss of stimulus detail.

She had in fact discovered the loss of sensitivity to high spatial frequency information that Kelly (1983) documented 50 years later. Indeed, Lehmann's stimuli and those of Leibmann were small, subtending about 2.0°; so small that the vertical shaft and oblique cross bars of the Zollner figure, for example, became one blurred vertical bar at equiluminance. Lehmann also noted that the degree of loss depended on the colour pair she used. Some colours, such as red and green, she called hard colours and while others, yellow and blue, she called soft colours since images formed between these colours and a white background (or vice versa) were more apt to be blurry, instable or disappear. This distinction is undoubtedly related to the very low spatial resolution for contours that differentially stimulate only the B cones (tritanopic borders, see Boynton, 1978).

Fifty years later, Gregory (1977, 1979) re-examined many of the same illusions and described an optical technique for producing equiluminous images. His stimuli, however, subtended large visual angles so that the image details were never lost. He reported that illusion strengths (with two exceptions, the Munsterberg or Café Wall illusion and the related Fraser spiral) were undiminished at equiluminance.

In 1987 Livingstone and Hubel measured many of these same illusions once more but claimed that all the illusions disappeared at equiluminance. The likely explanation of the loss in the illusions is the fine lines used to present their illusion stimuli. The visibility of thin chromatic lines drops drastically outside the central fovea reducing the effective spatial extent of the figures and therefore the strength of the illusions (the loss in visibility with eccentricity is significantly more pronounced with chromatic than luminance stimuli, Mullen, 1991). The poor visibility of chromatic lines (relative to luminance-defined lines) outside the fovea is otherwise not very noticeable, however, because with foveation they regain visibility.

I have measured the strengths of four of geometrical illusions (Zollner, Poggendorf, Ponzo, and vertical/horizontal illusions, Cavanagh, 1986, 1989) using large figures subtending over 8° of visual angle and having line widths of about 0.5° so that all of the figure detail was visible over its entire extent at equiluminance. All the illusions retained their full strength at equiluminance. In fact, these stimuli produced illusions of the same strength whether defined by luminance, by colour, by binocular disparity (random-dot stereograms, as also shown by Julesz, 1971), by texture or by motion (kinematograms). The figures in the last four cases – colour, stereo, texture and motion – are all equiluminous in that the mean luminance of the figure is equal to that of the background. Whatever the mechanisms that produce these illusions, they evidently operate on equiluminous images. This argues strongly for the preservation of the illusions in equiluminous colour stimuli: It is hard to imagine that the illusion would be lost only for presentation in equiluminous colour but not for other modes of equiluminous presentation.

The evidence therefore indicates that images defined by colour alone can provide contour information to the processes that determine shape, orientation and 3D structure and that these processes produce the same distortions of apparent shape for colour images as for luminance images.

Is it Possible to Produce Equiluminous Images?

Chromatic Aberration

Chromatic aberration always produces problems whenever high spatial frequencies are involved as the observer can control the relative contrast of the stimulus colours by changing accommodation to bring the different colours independently into focus. The contrast of the out-of-focus image colours is reduced by blurring and the finer the detail (the higher the spatial frequency content) of the image, the greater the loss. One technique to control chromatic aberration is therefore to blur the image to reduce the high spatial frequency content. Alternatively, images can be embedded in random luminance noise to mask the edge artefacts as well as most of the high spatial frequency detail of the image (Troscianko, 1987). On the other hand, if high spatial frequency detail is essential, observers must be corrected for chromatic aberration. If a two-element lens is used for correcting the axial aberration, then the relative scales of the different coloured images must be adjusted to compensate for the differential magnification introduced by these lenses. Alternately, a lens that does not introduce differential magnification (Powell, 1981; Howarth and Bradley, 1986) can be used. These lenses introduce other problems since alignment to the optical axis of the eye is extremely critical to the extent that even a bite bar does not guarantee adequate stability (Bradley *et al.*, 1989; Charman, Chapter 7).

Individual Variation

There are substantial differences in mean equiluminance settings between individuals with normal colour vision (Crone, 1959; Cavanagh *et al.*, 1984a). In any task, adjustments to determine equiluminous colours must be made individually for each observer.

Retinal Inhomogeneity

Equiluminance settings vary as a function of eccentricity (Livingstone and Hubel, 1987) although the variation of settings for red and green colours is relatively small (Mullen, 1991; White and Muermans, 1990). On the other hand, blue should be avoided, if possible, in constructing equiluminous images because of the extreme inhomogeneity of blue absorption across the retina, not only inside *vs* outside the 2° macular area but within the macula as well. It would be difficult to produce a uniformly equiluminous stimulus of more than 0.5–1° in size when blue is involved, and even in this case, fixation would have to be carefully maintained (although see the tritanopic procedure below). The problem would be less serious if blue areas of the stimulus were completely outside the macular region, but again, fixation would have to be carefully controlled to prevent the blue portions of the stimulus from falling within the macula.

Interunit Variability

A luminance pathway is a non-opponent system that sums cone signals. Because it sums signals, it will have a null response to an 'equiluminous' stimulus: a stimulus made up of two differently coloured waveforms that produce equal and opposite modulations of the cone signals to be summed. If the perception of motion depends only on signals defined by luminance, an 'equiluminous' stimulus can still produce a response if the extraction of luminance from the original cone signals is imperfect. One likely imperfection is that different units in the luminance pathway have different equiluminance points (due to different weights in the summation of the cone signals). If the null or equiluminance point varies across units, then there will always be some units responding no matter what the relative luminances of the two colours. Only if all units have the identical equiluminance point is it possible to produce a colour stimulus which does not activate a luminance pathway.

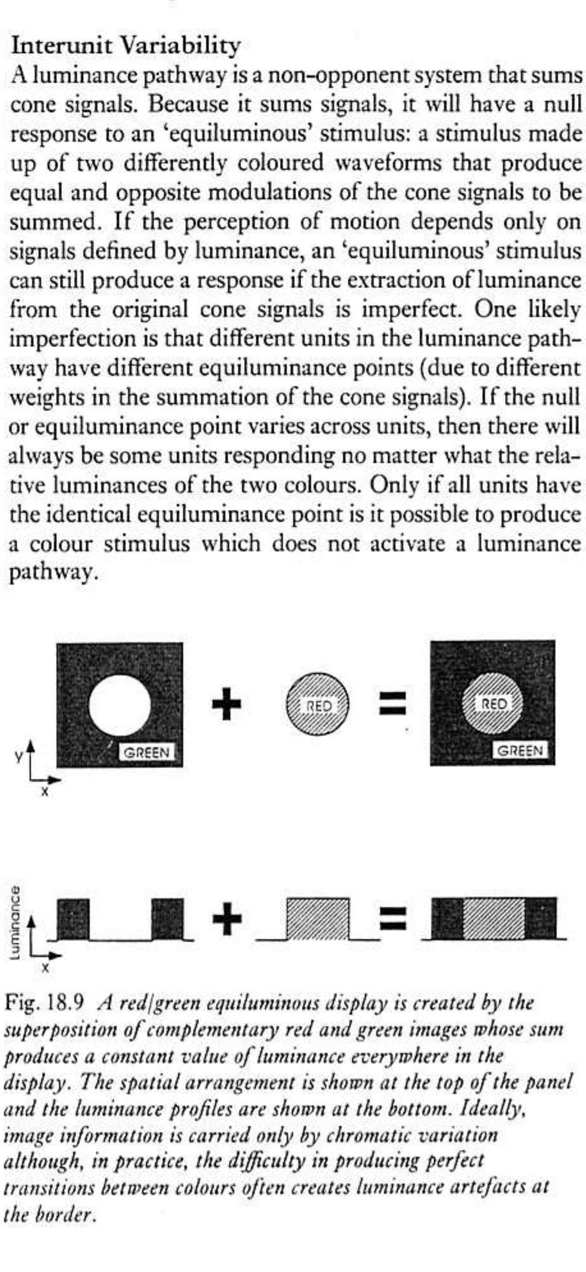

Fig. 18.9 *A red/green equiluminous display is created by the superposition of complementary red and green images whose sum produces a constant value of luminance everywhere in the display. The spatial arrangement is shown at the top of the panel and the luminance profiles are shown at the bottom. Ideally, image information is carried only by chromatic variation although, in practice, the difficulty in producing perfect transitions between colours often creates luminance artefacts at the border.*

Shapley and Kaplan (1989), Logothetis *et al.* (1989) and Lee *et al.* (1988) have shown that individual magnocellular units do show a minimum activity point at a particular luminance ratio between the two colours of their stimulus and that this minimum ratio varies somewhat from unit to unit. The contribution of this interunit variability to the effectiveness of equiluminous stimuli has been tested in a motion paradigm (Cavanagh and Anstis, 1991). The results showed that although the effect of interunit variability in equiluminance was undoubtedly present, it accounted for only a small portion of the overall contribution of colour to motion.

Task Effect or Spatial and Temporal Frequencies Effects?

Livingstone and Hubel (1987) have reported considerable variation in the equiluminance settings across tasks, suggesting that the different tasks might be evaluating different luminance subsystems. However, these tasks involved stimuli of different spatial and temporal frequency content and equiluminance settings are known to vary as a function of spatial and temporal frequency (Cavanagh *et al.*, 1987a). Ideally, to compare the equiluminance setting between two tasks, both tasks should use the identical stimulus but measure equiluminance through different criteria. For example, the same spatiotemporal stimulus can be used for either minimum flicker or minimum motion settings of equiluminance (Cavanagh *et al.*, 1987a). The results showed that the equiluminance settings were very similar for minimum motion and for minimum flicker when the same spatial and temporal frequencies were involved. This suggests that if one task is used to set equiluminance, the setting may not be valid in a second task unless the spatiotemporal nature of the stimuli in the two tasks is identical. For example, a minimum flicker task should not be used to set equiluminance for a subjective contour figure. Minimum flicker settings are most often performed at 15 Hz while subjective contours are typically evaluated in static images. Colours that are equiluminous in the first task may not remain equiluminous in the second.

Eye Movements

One final difficulty in producing equiluminous stimuli is the interaction between eye movements and chromatic adaptation. An image that is red on the left and green on the right will produce significant chromatic adaptation. With each eye movement, some stimulus regions of one colour will fall on retinal areas adapted to the other colour and this adaptation may change not only the apparent colour of the region but also the effective luminance. The heightened colour saturation around chromatic borders is a result of this adaptation and is part of the subjective phenomenon of jazzy, unstable borders. The differences in the temporal variation of the stimulus at different locations also produce luminance artefacts. Near borders, the colour falling on a particular retinal location alternates rapidly due to small eye movements. In areas of uniform colour, on the other hand, small eye movements produce no change in colour. Different temporal characteristics imply different equiluminance settings so that the image cannot be equiluminous over its entire extent.

Does Residual Luminance Response Explain Spatiotemporal Performance with Equiluminous Stimuli?

One explanation of the observations of shape, motion or depth percepts in response to equiluminous stimuli is that the luminance pathway is not capable of completely ignoring colour signals – colour signals 'bleed' into the luminance channel due to one or several of the factors mentioned above. Where it has been possible to test these luminance response to 'equiluminous' stimuli (Cavanagh and Anstis, 1991), the results showed that the combined effect of all these factors amounted to about one-third of the contribution of colour to, in this case, motion. Only in experiments where luminance stimuli oppose chromatic stimuli (Favreau and Cavanagh, 1981; Gorea and Pappathomas, 1989; Flanagan *et al.*, 1990) or where the chromatic response is qualitatively different from that for luminance stimuli (stereomotion, Tyler and Cavanagh, 1991; threshold elevation, Bradley *et al.*, 1988) can the possibility of residual luminance responses be ruled out.

How to Produce Equiluminous Displays

How to set equiluminance

When two-colour images are to be used at equiluminance in some task, some procedure must be chosen to equate the luminances of the two colours (the exception is the tritanopic technique described below). Photometric equiluminance (as measured by a photometer with the CIE V_λ characteristic) is never acceptable because of the large individual variations from this average reference point (Kaiser, 1988). There are several possibilities for making individual settings, including tests such as minimum flicker (Wagner and Boynton, 1972; Troscianko and Low, 1985), minimally distinct border (Wagner and Boynton, 1972), minimum motion (Anstis and Cavanagh, 1983; Cavanagh *et al.*, 1987a), slowed motion (Moreland, 1982), or minimum subjective contour (Cavanagh *et al.*, 1987b), to name a few. None of these is entirely satisfactory, however, since each may involve spatial and temporal frequencies and stimulus sizes that are different from those to be used in the task of interest and, as mentioned above, these factors all affect the equiluminance setting. In addition, it is a theoretical question, as yet unresolved, whether different tasks might have different equiluminance points even when using identical stimuli.

Given these difficulties, it is preferable to use several relative luminances between the two colours in the display during the experiment and to measure performance at each setting. If the task has degraded performance at some equiluminance setting, it will show up at some point within the test range. If the stimuli are highly saturated, the dip in performance, if any, near equiluminance is generally quite broad (e.g. Cavanagh *et al.*, 1984b) so that sampling at intervals of 5% luminance contrast over a range of ±20% around photometric equiluminance should be adequate.

Two-Colour Images

The creation of a red/green stimulus that produces an equal response in the luminance pathway at all points poses several technical problems. In order to produce a red disc on a green background, for example, a red image of a disc is combined with a background that is green everywhere except in the disc (Fig. 18.9). Reproducing this sharp colour transition on a cathode ray display or by optical means requires perfect alignment of the different colour images to avoid light or dark colour fringes at the borders. Even when the colour images are correctly aligned, the chromatic aberration in the eye will produce a strong luminance artefact at any sharp colour transition and this can only be corrected with an appropriate achromatizing lens (Powell, 1981), and even then the correction is imperfect (Bradley *et al.*, 1989). The effect of chromatic aberration can be reduced by embedding the image in random luminance noise to mask the edge artefacts (Troscianko, 1987) or by avoiding sharp transitions in the image, for example, with low-pass filtered images or low-frequency, sine waves (lower than $2\,\mathrm{c\,deg^{-1}}$, Cavanagh and Anstis, 1991). For low-pass filtered images or low-frequency sine waves, the accurate presentation of the gradual transitions between colours requires a high degree of linearity in the contrast response of the display.

The effects of retinal inhomogeneity and transverse chromatic aberration (Kulikowski and Walsh, Chapter 16) argue for using images of restricted sizes, say, less than 10° of visual angle.

Video

Despite these difficulties, it is relatively easy to use computer controlled video displays to produce images that approach equiluminance. If only two colours are used then the luminance of one colour can be adjusted by the observer through a range including equiluminance. The degradation of image quality that accompanies equiluminance occurs in a fairly broad range of contrasts near equiluminance (say ±5% luminance contrast) so this display technique is sufficient to observe the more dramatic

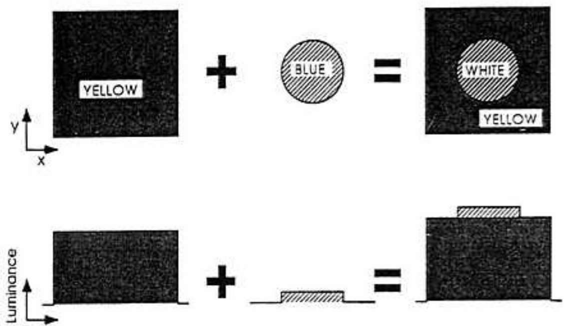

Fig. 18.10 *A tritanopic display is created by the superposition of a blue image and a uniform yellow adapting field. The spatial arrangement is shown at the top of the panel and the luminance profiles are shown at the bottom. The bright yellow field creates a high luminance baseline so that the variation in luminance in the blue image is pushed below the lumiunance contrast threshold. Only the B cone responds differentially to the image information, rendering the image effectively equiluminous. Since only one coloured image varies spatially, no artifacts occur at the chromatic borders. Neither chromatic aberration, colour misalignment, non-linear response of the display or the neural pathways, nor retinal inhomogeneities will produce a luminance artefact.*

effects. Each colour's luminance can be independently controlled in the display if at least 8 bits of intensity resolution are available. If the display device does not have 8 bits intensity resolution, an external attenuator can be placed between the graphics controller and the monitor that effectively acts as an independent brightness control for the red, green or blue signal. The disadvantage of this approach is that it affects the entire display area; it cannot be used to brighten or dim one colour in only one portion of the display.

If graded colours are required in the stimulus, such as in the smooth transitions of a sine wave, then the demands on the display device are much more severe. The graphics controller must have at least 8 bits of intensity resolution and the luminance output at the screen must be linearized. Cowman (1983) describes the steps necessary to calibrate a colour monitor.

Slides

A less expensive way to present equiluminous images is to prepare slides with test images (subjective contour figures, random-dot stereograms, illusion figures, etc.) in two colours, say red on green, where each colour has a uniform intensity wherever it appears on the slide. It is not practical to hope that the two colours would be equiluminous when projected but a variable colour filter can be placed in front of the projector lens to bring the two colours to equiluminance. Variable colour filters are available from photographic supply stores but a more effective filter can be produced as a transparency that varies, in the case of red/green slides, from light green on one end through pale yellow to pinkish on the other end. Simply place red, yellow and green papers side by side and photograph them very much out of focus. Have a photo lab produce a large (20 × 25 cm) transparency from this. This will transmit a great deal more light than a commercial filter and still give enough range to bring most red/green slides to equiluminance. Only two-colour images can be viewed this way. An additional advantage is that the projector can be defocused to reduce edge artefacts.

Cut Outs

A more laborious method, originally used by Liebmann (1927), requires cutting the images to be viewed out of cardboard (or producing white photostats on transparencies). Again only two colour images can be displayed. One colour is projected against a background screen and the second colour is projected on a nearer screen out of which the image shapes have been cut and through which the background is visible. The two projectors are aimed at the two screens from the side and the screens are sufficiently separated so that each beam falls only on the intended target. The relative intensity of the two beams can be controlled with a variac and the colours chosen with filters placed in the beams.

Tritanopic

There are two principal chromatic pathways: a red/green one and a blue/yellow one. The interesting characteristic of the blue/yellow pathway is that it is strongly driven by input from the B cones. These cones, on the other hand, contribute little or no signal to the luminance pathway (Eisner and MacLeod, 1980; Cavanagh *et al.*, 1987a) especially at suprathreshold levels (Stockman *et al.*, 1991). This provides an opportunity for generating equiluminous stimuli with few of the problems posed by red/green stimuli. As originally described by Stiles (1959) and Wald (1966), an intense yellow adapting field superimposed on a deep blue image can isolate the response of the B cones very effectively. The reason is that the yellow field drives the responses of the R and G cones to a very high level so that the slight response of these cone types to the spatial variations of the blue image now falls below the contrast threshold for these cones. Since the R and G cones are the source of the luminance signal, the luminance pathway will see only a uniform (bright) field and the image is effectively equiluminous. The image information is carried principally by the chromatic pathway. Since only the B cone responds differentially to such an image, it is called a tritanopic stimulus – it is invisible to a tritanope, an individual who is missing B cones.

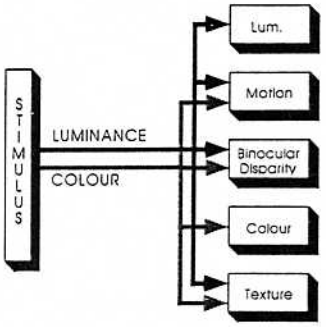

Fig. 18.11 *Pathways in early vision. Colour information contributes to texture, motion and binocular disparity analyses in addition to colour analysis. The contribution of colour to these analyses is less effective than that of luminance principally because of stimulus limitations; the sensitivity to chromatic stimuli may be several times higher than that to luminance stimuli (Stromeyer* et al., *1990). Both colour and luminance analyses make use of size and orientation coding primitives. Shape defined by explicit contours is signalled by all pathways but shape defined by implicit contours is only signalled by the luminance pathway.*

Notice that with this arrangement, there is only one spatially varying colour image, a blue one, and not two complementary images that have to be exactly aligned (Fig. 18.10). There is no requirement that two colours be exactly matched in subjective luminance at all points, since the small variations in luminance of the blue image are, because of the intense yellow field, below threshold. As a result, there are no edge artefacts: no effect of chromatic aberration, no effect of misalignment, and no linearity problem. Furthermore, retinal inhomogeneity no longer produces any luminance artifacts. The large retinal variation in response to blue because of macular pigmentation creates only a variation in the intensity of the chromatic image; any spatial variation in the luminance pathway comes only from the contribution of the B cones to luminance.

Several experiments have used this tritanopic technique to isolate B cone functions. Grinberg and Williams (1985) have reported that depth can be perceived in figural and random-dot stereograms presented in this manner. Stromeyer *et al.* (1979) demonstrated colour-specific threshold elevation and Lee and Stromeyer (1989) describe motion perception based on B cone responses.

This technique only produces an equiluminous stimulus if the B cones make no contribution to luminance. However, two more recent papers suggest that they do (Lee and Stromeyer, 1989; Stockman *et al.*, 1991;). The contribution is small though and gets even smaller at higher B cone modulation levels and, intriguingly, is in negative phase. Because of the very high level of activation of the luminance pathway by the yellow adapting field in the tritanopic technique, this contribution may have little actual effect in the stimuli that we shall use.

To produce a tritanopic display, intense yellow light can be shone directly on a CRT display while presenting images only with the blue phosphor. A slowly rotating stimulus on the display will slow down noticeably when the yellow field is sufficiently intense. The true speed of the rotating stimulus can then be seen by viewing the display through a blue filter (this blocks the yellow adapting field).

Because of the possibility of some activation of the luminance pathway by the B cones, this technique does not guarantee complete isolation of the blue/yellow chromatic pathway. Nevertheless, the major response to a tritanopic stimulus is carried by the chromatic pathway and the technique is easy to use and robust against display, eye and neural artefacts. It is certainly the only method for presenting near equiluminous stimuli to large audiences without having to worry about either aligning colour images or adjusting the display to find an equiluminance point for all observers. As a small added advantage, tritanopic stimuli appear the same to the 8% of males who have red/green colour vision deficiences (and for whom red/green displays are of little use) as they do to normal observers.

Equiluminance: What Is Really Lost?

The data I have reviewed show that chromatic information contributes to all early visual processes: motion, texture, depth, orientation and size (Fig. 18.11). There is, however, a severe loss in spatial and temporal resolution of images presented at equiluminance. This is the principal factor producing the impression of degraded vision for chromatic stimuli.

Even for stimuli that can be easily resolved, however, there is a relative loss in the perception of motion and binocular depth at equiluminance when compared to stimuli defined by luminance. These losses may be due to the inherent limitations of the chromatic contrast range at least in the case of red/green modulation. Luminance stimuli can modulate each cone class by as much as 100%, whereas the maximum differential modulation of the R- and G-cone classes attainable on a colour monitor is between 15 and 25%. In other words, the biggest loss for red/green chromatic stimuli may be a stimulus factor and not a processing factor: available luminance modulation (in-phase for R and G cones) is much grater than available chromatic modulation (out-of-phase for R and G cones) and this is due to the large overlap in the spectral sensitivity curves for the R and G cones. When sensitivity is scaled in terms of cone contrasts (Stromeyer *et al.*, 1990), the visual system is about four times more sensitive to the motion of equiluminous, red/green gratings than to that of luminance gratings. This is not the entire story, however, since cone contrasts can be very high for tritanopic stimuli (modulating only the B cones) and yet motion (Cavanagh and Anstis, 1991) and depth (Grinberg and Williams, 1985) perception is weak here as well.

There is a final loss that can be attributed to neither spatiotemporal resolution nor to effective contrast. The recovery of 3D shape is severely limited for images with implicit contours: shape from shadows and subjective contours (these are 3D in the sense that they are seen as overlapping surfaces). In general, surfaces are not easily linked together across equiluminous chromatic borders. A red and green surface appears as red patches floating on a green background (or vice versa), not as a single, red and green surface. The depth in an equiluminous random-dot stereogram is seen, for example, as some red dots in front at the centre and some red dots further back surrounding them, with a uniform green field at some depth behind all of them. Each closed red area is taken as a single piece and not grouped with adjacent areas. This absence of linking (Livingstone and Hubel, 1987) may indicate that an equiluminous colour boundary on its own is always interpreted as a surface boundary. Linking of surfaces occurs readily when there are both colour and luminance differences. Perhaps the presence of luminance allows local boundaries to be ignored (as they must be if they are due to shadows) and more global grouping to occur.

Equiluminance: What Is It Good For?

Several differences between the processing of luminance and chromatic information have been reviewed, principally differences in spatial and temporal resolution and in linking. The losses in spatial and temporal resolution may correspond to the availability of chromatic information in the environment and its usefulness in object recognition. On the other hand, the loss in linking of surfaces across equiluminous borders remains an intriguing puzzle.

Rather than these differences, however, it is perhaps the similarities in the processing of equiluminous and luminance stimuli that are most informative. They tell us a number of things about the overall strategies of the visual system in recovering scene information.

In particular, opposite after-effects can be elicited simultaneously for coloured gratings and luminance gratings in both tilt and size after-effect paradigms (Favreau and Cavanagh, 1981; Flanagan, et al., 1990). If we assume that the extraction of orientation and size is an initial step in the analysis of form, these results do not agree with Livingstone and Hubel's (1987) conjecture that colour and form are processed in independent cortical pathways. The after-effect results as well as the threshold elevation results of Bradley *et al.* (1988) imply that encoding of form does occur in pathways selective for colour, and in a manner similar to that which occurs within pathways selective for luminance.

It makes sense for the visual system to provide the colour pathway with a rich set of shape primitives (e.g. size and orientation) since the analysis of shape based on colour information can frequently be more useful than that based on luminance information. Colour edges reliably move with the objects while luminance edges are often confounded by the clutter of shadow borders that are unrelated to the objects across which they fall.

It also makes sense for these separate analyses to be similar. One important reason for the duplication of analyses may be the exchange of image information between analyses. If an integrated higher-level image is to be formed by combining lower-level images, it is advantageous to have all lower-level images defined in a standard format. Size and orientation coding may therefore be part of an internal standard for image exchange in the visual system.

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