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Vision with equiluminant colour contrast: 2. A large-scale technique and observations

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Abstract. A simple technique is described for producing large-scale, tritanopic displays. The technique reproduces the various phenomena of vision with equiluminous-colour contrast that have previously been reported with red/green stimuli. It is, however, much less demanding technically, robust against artifacts, and can be used on large-scale scenes. One advantage of the technique is that a piece of blue filter can be used individually by each observer to compare quickly tritanopic and luminance conditions.

1 Introduction

In order to study the properties of the chromatic and luminance pathways of vision, it is necessary to isolate each with appropriate stimuli. It is easy to examine the characteristics of the luminance pathway by using achromatic stimuli but it is very difficult to produce stimuli that activate the chromatic pathways but are invisible to the luminance pathway. Photometric luminance (eg cd m^{-2}) is conceptually a measure of the intensity of response in the luminance pathway but equal photometric luminance of two colours does not guarantee equal response to both in a luminance-based task for 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. The generation of a chromatic stimulus that produces an equal response in the luminance pathway at all points therefore raises several technical problems.

In order to produce a red disk on an equiluminous green background, for example, a red image of a disk is combined with a background that is green everywhere except for where the disk is (figure 1). Reproducing this sharp colour transition on a cathode ray display or by optical means (Gregory 1977) 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 artifact 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 (Zhang et al 1990). The effect of chromatic aberration can be reduced by avoiding sharp transitions in the image, for example with low-pass filtered images or low-frequency sine waves. In either case, the accurate presentation of gradual transitions between colours requires a high degree of linearity in the contrast response of the display. Finally, even if there are no edge artifacts in the image, the equiluminance point will vary as a function of retinal position (Livingstone and Hubel 1987; White and Muermans 1990; Mullen 1991) so that colours that are equiluminous in one region will not necessarily remain so in another region.

Equiluminous images involving the complementary spatial variation of two colours, such as red and green, are therefore particularly difficult to control; any source of difference in the response to the two colours, whether in the monitor, in the optics of the eye or in the physiology of the visual system, will produce a luminance artifact.

There is, however, an alternative method based on the isolation of the short-wavelength-sensitive cones (B cones). The luminance pathway takes its input principally from the sum of the long- and medium-wavelength-sensitive cones (R cones and G cones, respectively). The B cones make, if anything, only a small contribution to the luminance pathway (Eisner and MacLeod 1980; Drum 1983; Cavanagh et al 1987; Lee and Stromeyer 1989) and this contribution decreases to negligible levels when the B-cone stimulus is more than about twice its detection threshold (Stockman et al 1991). On the other hand, the blue/yellow chromatic pathway is strongly driven by input from the B cones. This provides an opportunity for generating near-equiluminous colour stimuli with few of the problems posed by complementary variations of two colours.

As originally described by Wald (1966) and Stiles (1959), 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 cones and G cones to a very high level such that the slight response of these cone types to the spatial variations of the blue image falls below the contrast threshold for these cones. Since the R cones and G cones are the principal 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 response of the blue/yellow chromatic pathway to the B-cone signals. Since only the B cones respond differentially to such an image, it is called a tritanopic stimulus—it is invisible to a tritanope, an individual who lacks B cones.

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 (figure 2). 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 artifacts: 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

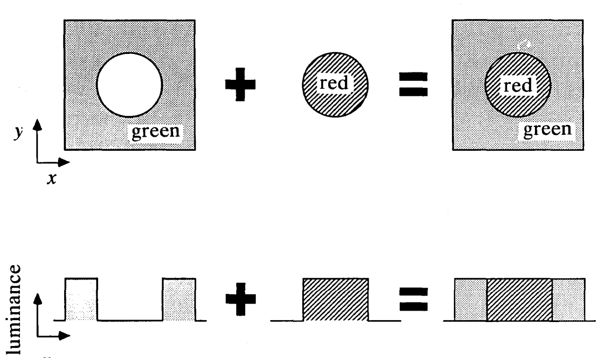

Figure 1. A red/green equiluminous display is created by the superposition of complementary red and green images whose sum produces a constant value of luminance everywhere in the display. The spatial arrangement is shown at the top of the figure, and the luminance profiles are shown at the bottom. Ideally, image information is carried only by chromatic variation although, in practice, the difficulty in producing perfect transitions from one colour to another often creates luminance artifacts at the border.

creates only a variation in the intensity of the chromatic image; it does not produce any spatial variation in the luminance pathway.

In several experiments this tritanopic technique has been used 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 (1980) demonstrated colour-specific threshold elevation and Lee and Stromeyer (1989) describe motion perception based on B-cone responses. Uusvaara and Rovamo (1988) have reported that the highest resolvable spatial frequency is about 3 to 4 cycles deg^{-1} for B-cone stimuli.

It is appealing to be able to isolate the B-cone response so easily, but does this also guarantee an equiluminous stimulus? That is, do the B cones make any contribution to luminance? Three papers suggest that they do (Drum 1983; Lee and Stromeyer 1989; Stockman et al 1991). The contribution, however, is small especially at the adaptation levels used in our displays and, intriguingly, is in negative phase (Lee and Stromeyer 1989; Stockman et al 1991). Because of the possible contribution of the B cones to the luminance pathway, we shall refer to the tritanopic stimulus as near-equiluminous rather than equiluminous.

Although it remains to be established whether the isolation of the chromatic pathways is total when this technique is used, it is clear that the major response is carried by chromatic pathways and that the technique is easy to use and robust against artifacts of the display, the eye, and the nervous system. 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, the 8% of males who have red/green colour vision deficiencies and for whom red/green displays are of little use have the same perceptions of tritanopic stimuli as do normal observers.

Because of the robustness of the technique and the availability of very large numbers of experienced observers in attendance at the Gregoryfest in Bristol, England, in September 1988, we decided to attempt a very large-scale tritanopic demonstration in the Winston Theatre of the University of Bristol Student Union.

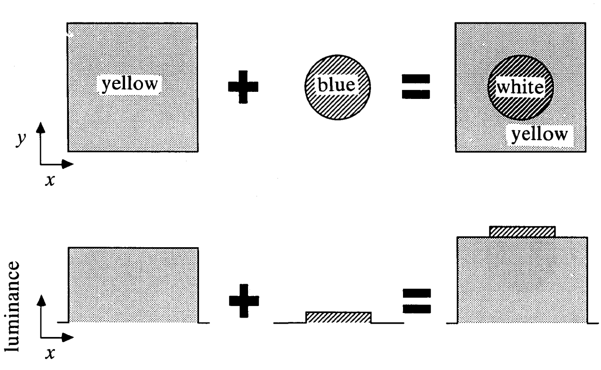

Figure 2. A tritanopic, near-equiluminous display is created by the superposition of a blue image and a uniform yellow adapting field. The spatial arrangement is shown at the top of the figure, and the luminance profiles are shown at the bottom. The bright yellow field creates a high luminance baseline so that the variations in luminance in the blue image are pushed below the luminance contrast threshold. Only the B cones respond differentially to the image information thus rendering the image near-equiluminous. Since only one coloured image varies spatially, no artifacts occur at the image borders. Neither chromatic aberration, colour misalignment, nonlinear response of the display or the neural pathways, nor retinal inhomogeneities will produce a luminance artifact.

2 Method

We constructed an 'equiluminizing' curtain (3 m × 3 m) from a large, transparent veil hung in front of an equally large, blue filter (figure 3). Uniform yellow light from several theatre spotlights was reflected back from the veil to the audience but was blocked from the scene behind this veil by the blue filter. The scene itself was illuminated in blue light and was visible to the audience through the filter, the veil, and the veiling yellow luminance. With the help of the staff of the University of Bristol Student Union we set up several display scenes of approximately 3 m × 3 m in size and about 3 m deep. The purpose of these demonstrations was to evaluate the perception of binocular and monocular depth cues in tritanopic, near-equiluminous scenes.

Several objects were arranged on the stage behind the screen (not all at the same time): two white rectangles placed at different depths; a three-dimensional (3-D) wire-frame cube with sides of about 80 cm perched on one of its vertexes; a white disk 1 m in diameter with six black radial spokes rotating at approximately 6 rev min^{-1}; and a large Ames window, rotating slowly with a sword placed through one pane of the window.

These objects were illuminated by two halogen 1000 W barn-door floodlights through deep blue filters (Lee 120) which transmitted wavelengths below 510 nm. The light reflected from the objects then passed through a blue filter (3 m × 3 m) (also Lee 120), through the equiluminizing screen and to the observers. The screen was also illuminated from the front by 3 Strand Cadenza 9/15 focus spots of 2000 W each. A deep orange filter (Lee 158) was placed in the beam of each spot. This filter transmitted wavelengths above 470 nm. The screen was a square (3 m × 3 m) piece of see-through curtain material (fine mesh) that allowed the scene behind the screen to be viewed with little or no diffusion and at the same time reflected the yellow light back to the observers. The yellow light could not pass through the equiluminizing screen to fall on the scene behind it, however, as the blue filter was effectively opaque for this light.

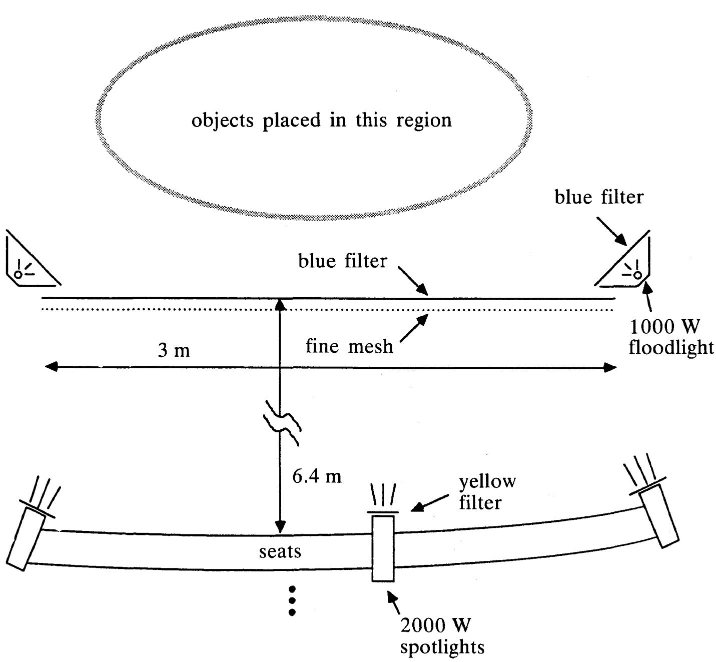

Figure 3. Spatial layout of the Gregoryfest test scene viewed from above. The fine mesh must be textureless and be stretched taut over the frame of the screen.

The observers were each given a piece of the blue filter about 10 cm × 3 cm in size that enabled them to quickly compare tritanopic and luminance conditions. When held over the eyes, the blue filter blocked the yellow veiling luminance and revealed a light and dark blue image defined by luminance contrast. Without the blue filter, the scene returned to near equiluminance.

Since motion of equiluminous stimuli is noticeably slower (Moreland 1982; Cavanagh et al 1984), the apparent speed of a large, rotating disk was used to set the brightness of the blue light so that the luminance variation in the scene remained below threshold. The intensity of the blue lights was increased until the rotation speed appeared normal (eg the same speed as when the disk was viewed through the additional hand-held, blue filter), and then the intensity was reduced until the apparent speed dropped noticeably. Following this adjustment, the mean luminance of the bright surfaces behind the screen when viewed from the theatre seats was approximately 3.0 cd m^{-2} whereas that of the dark areas was about 1.5 cd m^{-2}. The relatively high luminance in the dark areas was due to the diffuse scattering of light from the scene by the front screen. This scattering was fairly uniform in brightness across the screen. The mean luminance of the yellow adapting field was 75 cd m^{-2}. The luminance contrast of the objects was therefore about 1%. Although this value apears to be at or above the contrast threshold for luminance further decreases in the luminance of the blue image beyond this point produced no additional losses of depth or motion. Quite possibly, the chromatic variations in the image were masking luminance variations, and thus increasing the thresholds. For example, De Valois and Switkes (1983) report that the presence of red/green chromatic stimuli raises the threshold for luminance stimuli to 2.5%.

3 Results and discussion

The majority of observers saw little or no depth in the scene. Several commented that the objects appeared to be painted on the front screen or perhaps a few centimetres behind it. Some observers reported that when the yellow lights were extinguished (revealing the objects in luminance contrast) the objects appeared to recede quickly in depth and to increase in size. The disparities in the scene varied with seat location but were as much as 8.0 min arc (relative to the front screen), well above the disparity threshold of 0.7 min arc reported by Grinberg and Williams (1985) for B-cone stimuli.

The observers reported that the large 3-D cube could be seen as a 3-D structure, and reversed easily in depth. However, they all agreed that the depth impressions were more like those produced by a 2-D drawing of a Necker cube. When asked to identify which corner of the cube was actually in front, they responded at chance level. When asked to perform the same task while looking through the blue filter, all observers identified the correct corner.

The rotating disk was uniformly seen to slow down without the blue filter (tritanopic condition) and to speed up when viewed through the filter (luminance). The Ames window apeared to oscillate back and forth when viewed in near-equiluminance just as it did when viewed with luminance contrast although it did seem to oscillate faster in this latter condition.

Finally, only large-scale features of the scenes were visible through the equiluminizing curtain. The very low spatial resolution is consistent with the low sampling density of B cones on the retina. However, this factor was not the only contributor to the loss of detail. Brindley (1953) previously reported that the contrast range for tritanopic colours (differentially stimulating only the B cones) is extremely compressed and we also noted that images appear to have virtually only two levels (bluish-white and yellow). Smooth gradations of brightness in the scene were often lost, appearing more as discrete steps. These effects limit the range of images that can be examined in a tritanopic display without loss of visibility to those with high contrast and no fine detail.

Following the large-scale experiment, we built a smaller version with a screen of about 60 cm × 60 cm, and the objects were placed up to 60 cm behind the screen. Observers viewed the objects from a distance of about 20 cm in front of the screen. The disparities relative to the front screen could be up to 6 deg arc under these conditions and yet the phenomenon of seeing the objects as painted or projected on the front screen persisted. A much greater range of lighting conditions was available with this smaller display but the loss of depth was always present under lighting conditions that also produced a noticeable slowing of a rotating test disk. Therefore, it does not appear that either disparity or contrast thresholds can explain the loss of depth perception.

Finally, in the Media Lab at MIT we constructed the largest screen, 8 m long and 2 m high, in order to offer near-equiluminous viewing to the public during ChromaFest '90. Several objects were again arranged behind the screen, and the display area was also open to the public who then appeared to be 'equiluminized' to the viewers on the other side. The same filters were used, and 16 000 W of yellow light were directed at the screen producing a luminance of 65 to 90 cd m^{-2} of reflected yellow light. The luminance of the blue light transmitted through the screen was 1.0 to 1.4 cd m^{-2} for the bright areas of the scene and 0.25 to 0.40 cd m^{-2} for the dark areas. This again corresponded to somewhat less than 1% luminance contrast. Slowed motion and reduced depth were again evident.

Although the observation of slowed motion perception is consistent with previous reports (Moreland 1982; Cavanagh et al 1984), the reduced depth-perception is not (Grinberg and Williams 1985). It is possible that the faint textures of the equiluminizing screen produce a local disparity signal that 'captures', or overrides, that from the more distant, near-equiluminous objects. A similar effect has been reported by Spillman and Redies (1981) where a subjective figure appeared to lie in the plane of a textured overlay held above the figure. In the study by Grinberg and Williams (1985), the adapting yellow field was superimposed by using a half-silvered mirror and should not have had any visible texture at any depth. Stereo capture implies that if binocular depth signals are produced by chromatic stimuli, these signals are easily overcome by competing luminance-based disparity signals. In other words, situations that would produce impressions of transparency for two planes of luminance-defined stimuli (a transparent screen in front of objects) do not do so when the second plane (containing the objects) is defined by equiluminous colour contrast. This has been verified directly in a separate paper (Watanabe and Cavanagh 1992).

Whatever the cause of the loss of binocular depth perception, it is clear that this loss did not affect the perception of monocular depth cues. In several cases, stimuli that were actually 3-D objects appeared to be projected as a 2-D image on the screen but maintained their 3-D interpretation as if they were seen as drawings. For example, a 3-D cube appeared to be presented as a flat line-drawing which nevertheless produced the same 3-D impression that a line drawing of a Necker cube would generate. The figure could be reversed in depth and, in fact, this reversal was easy to perform with binocular viewing. With luminance contrast, on the other hand, it is difficult to reverse the depth of a 3-D Necker cube because of conflicting binocular cues. Similar results were found for the Ames window. That is, the 3-D impressions that could be obtained with monocular viewing in the luminance condition were equally available in the tritanopic condition with binocular (or monocular) viewing.

In summary, the tritanopic technique reproduces many of the phenomena of vision with equiluminous-colour contrast that have previously been reported with more demanding techniques. Since only a single coloured image is required, the stimuli can be presented on an ordinary television display and even reproduced from videotape. Simply overlay the monitor with a blue filter and a piece of fine mesh and direct a slide or overhead projector with a yellow filter in its beam onto the monitor screen. If a colour monitor is used and the image can be limited to the blue phosphors, the blue filter is unnecessary. The brightness of the yellow adapting field can be controlled by varying the distance of the projector from the screen, and a slowly moving stimulus in the display can serve as an indicator that luminance contrast has dropped below threshold. A corresponding arrangement can be made for viewing slide images.

An advantage of the technique is that a piece of the blue filter can be used individually by each observer to compare quickly tritanopic and luminance conditions. The blue filter blocks the yellow veiling luminance and reveals a light and dark blue image that is defined by luminance contrast. Without the blue filter, the scene returns to near equiluminance.

Finally, the most significant advantage of the technique is that it can be used on real scenes by interposing the equiluminizing curtain between the audience and the scene.

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