Interactions between colour and luminance contrast in the perception of motion

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It has been demonstrated widely that at isoluminance moving chromatic stimuli are seen to be stationary or moving more slowly than their luminance counterparts. We have examined the effect on perceived velocity of adding luminance contrast to an isoluminant chromatic stimulus. We show that moving luminance contrast 'captures' colour so that a combined colour and luminance stimulus is seen moving as a unified percept. However, in the presence of colour contrast, significantly higher levels of luminance contrast are required to achieve a veridical velocity than for monochromatic stimuli with only luminance contrast. We show that this interactive effect between colour and luminance contrast cannot be fully explained by a threshold masking of luminance by colour contrast. The effect suggests that a breakdown in the veridical perception of velocity should be expected for colours with a wide range of associated luminance contrasts and not just for those at the point of isoluminance.

There is a considerable body of evidence which suggests that colour vision is impaired in the processing of motion[1–5]. Although it is now well known that moving isoluminant chromatic stimuli may be perceived as stationary, moving more slowly than their luminance counterparts, or as moving jerkily, the motion deficit of colour vision is neither a simple nor a complete one. Under certain conditions, the chromatic properties of visual stimuli may still contribute to the perception of motion, to the motion after-effect or to the identification of direction[6–11].

It is interesting that in the normal visual world, in which isoluminant conditions occur very rarely, we are not aware of any asynchrony in the perception of motion from chromatic and luminance contrast. It has been assumed that even small amounts of luminance contrast associated with the colour differences in the image will be sufficient to unify the perceived motion of the colour and luminance aspects of the scene. This implies that there are interactions between colour and luminance contrast effective in influencing the perception of motion.

It has been shown that the 'capture' of colour by moving luminance contours can be induced by quite complex cues; for example, moving random dot patterns or illusory borders have been reported to induce the perception of motion in stationary chromatic borders[12], particularly when eccentrically viewed. In this paper we investigate the contribution of luminance contrast to the motion of chromatic stimuli under much simpler conditions. We have used drifting sinusoidal stimuli in which the colour and luminance contrast are spatially co-extensive and overlaid. A velocity matching technique is used to measure the perceived velocity of the stimulus for different combinations of colour and luminance contrast.

We find that luminance contrast needed to produce smooth motion at a veridical velocity is significantly greater when the stimulus has colour contrast than when luminance contrast is present alone. This negative influence of the chromatic content of visual simuli on the perception of motion indicates that luminance contrast does not contribute solely or independently to the motion task. We find that high levels of luminance contrast (generally greater than $10\times$ detection threshold) are required before chromatic stimuli are perceived to move at their veridical speed. Thus it remains curious that, despite the wide range of colour and luminance contrasts in the natural scene, discrepancies in the perceived speeds of the colour and luminance aspects of the same object are never apparent.

Methods

Full details of the stimuli, apparatus and psychophysical methods have been described elsewhere and are given only briefly here[5,13]. Red–green sinusoidal chromatic test

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gratings with a spatial frequency of 1 c/deg and a drift rate of 1.6 Hz were displayed using two Joyce display monitors (DM2), viewed through interference filters (602 and 526 nm), and combined in antiphase. Longitudinal and transverse chromatic aberrations were corrected[14]. Luminance test gratings were monochromatic (526 nm) and presented under the same spatial and temporal conditions as the chromatic stimuli. The contrasts of the red and green luminance gratings are equal to each other, and their contrast defines the contrast of the chromatic grating. All stimuli were presented vertically in a hard edged black circular patch with at least three or four spatial cycles displayed, and were centrally fixated using a very small fixation spot. Stimuli had a mean luminance of 42 cd m^{-2}. Results were obtained on two subjects (the authors).

Isoluminance of the two colours was measured using a minimum motion method in which the perceived drift rate of a fixed high contrast grating was measured as a function of the ratio of the red to green mean luminance in the stimulus[5]. This reveals a sharply defined minimum in perceived drift rate at the isoluminant point.

Perceived velocity was measured using a velocity matching technique. The standard stimulus was an achromatic (black and white) grating at a contrast of 17.8% and with the same spatial parameters and mean luminance as the chromatic test grating. Its direction of drift reversed regularly. The drift rate of the standard stimulus could be varied by the subject using a method of adjustment. The test and standard gratings were simultaneously displayed but arranged so that they were not simultaneously visible. The subject was instructed to fixate carefully the test and standard stimulus in turn and to adjust the drift rate of the standard to match the perceived drift rate of the chromatic grating. Results are for at least three to five threshold settings made non-sequentially.

Results

The perceived velocity of luminance contrast

We first investigated how the perceived velocity of luminance-only gratings depends on their luminance contrast. In *Figure 1* matched temporal frequency is shown as a function of luminance contrast, which is expressed in multiples of detection threshold. The results show that perceived drift rate initially increases with the contrast of the stimuli. This increase has been fitted by linear regression and extrapolated to the veridical drift rate of 1.6 Hz. For both subjects a luminance contrast of 6.5 or 7 × threshold is required before the motion is perceived at its veridical rate. This veridical drift rate represents an asymptotic speed; although not shown here, the matched temporary frequency does not rise above the veridical value for these stimuli[13].

When replotted with the same format, the results of Thompson[15] are similar in form to ours. There is, however, some quantitative disagreement since Thompson finds the dependence of perceived speed on contrast extends to higher contrasts (around 0.5 log units greater).

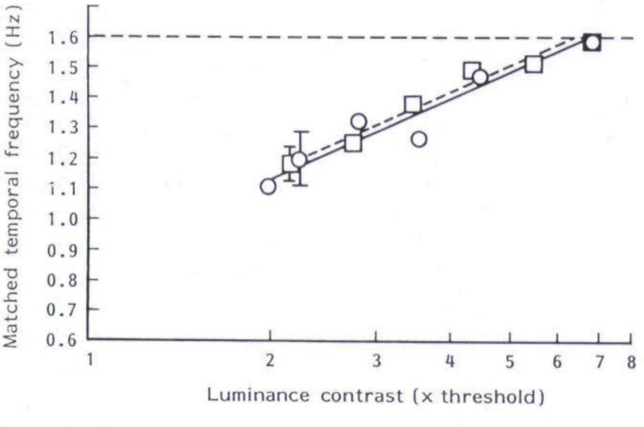

Figure 1 Test stimuli are luminance-only gratings. Matched temporal frequency is plotted as a function of luminance contrast, expressed as multiples of threshold. Detection threshold was measured for each subject. The dashed line indicates the true drift rate. The functions have been fitted by linear regressions. Data for two subjects: ○, J.C.B. and □, K.T.M. Error bars indicate ±1 SD.

The perceived velocity of combined colour and luminance contrast

We next investigated the effect on perceived velocity of adding luminance contrast to an isoluminant chromatic grating. Luminance contrast was induced in the chromatic stimuli by increasing the contrast of the green component grating relative to the red. Results are shown in *Figure 2* for a range of different chromatic contrasts. The chromatic contrast given on the figures refers to the contrast of the chromatic stimulus at isoluminance, as adding luminance contrast has the effect of slightly increasing the colour modulation.

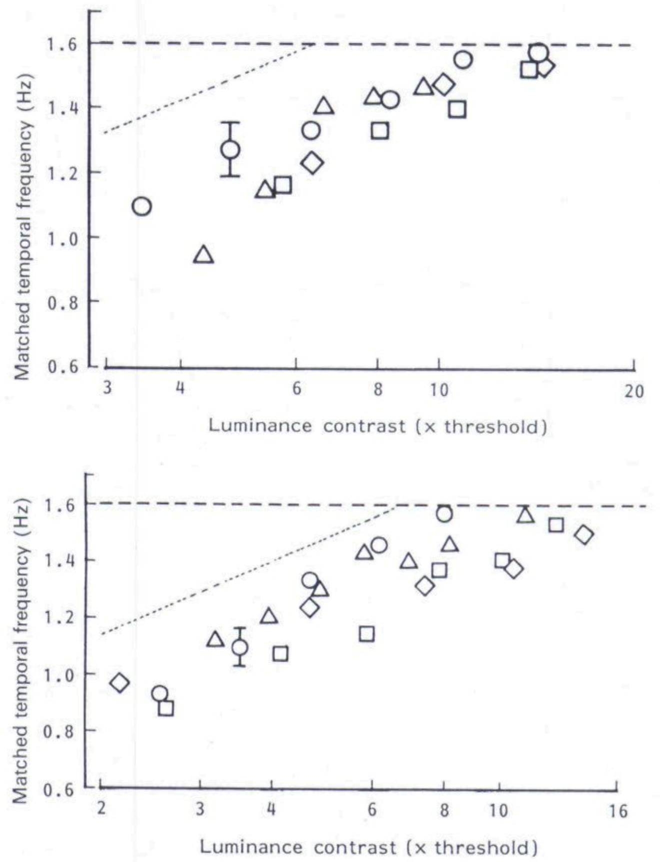

Figure 2 Test stimuli are chromatic gratings to which luminance contrast is added. Matched temporal frequency (Hz) is plotted as a function of the luminance contrast (in threshold multiples) in the chromatic stimulus. Different symbols show different colour contrasts (expressed as percentage colour modulation in the isoluminant stimulus): ◇, 31.6%; □, 17.8%; △, 5.62%; ○, 1.78%. The horizontal dashed line gives the true drift rate. The fine dashed line indicates the results for luminance-only gratings taken from *Figure 1*. Results for two subjects: K.T.M. (above) and J.C.B. (below)

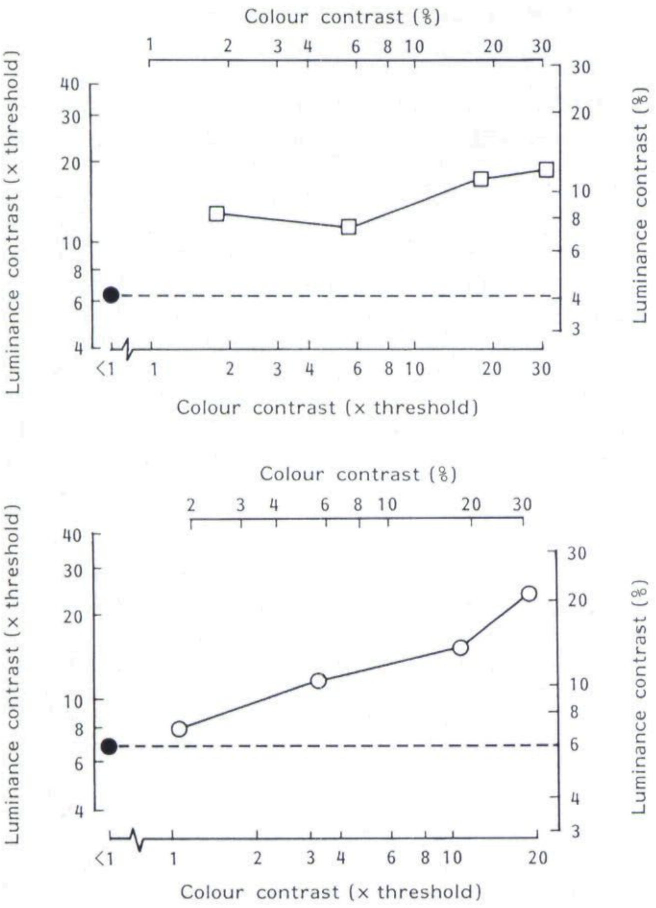

Figure 3 The luminance contrast (in threshold multiples) required to obtain a veridical drift rate of the chromatic stimuli, plotted as a function of their colour contrast (in threshold multiples). The luminance contrast at the veridical drift rate was obtained from *Figure 2* by fitting the data for each colour contrast by linear regression. The right hand and upper axes give the luminance and colour contrasts as a percentage, respectively. The solid symbol and dashed line indicate the luminance contrast required for a veridical velocity in the absence of colour contrast (taken from the data of *Figure 1*). Results for K.T.M. (above) and J.C.B. (below)

At isoluminance the perceived motion is not smooth and no velocity match can be made[5]. However, we find that quite low luminance contrasts in the chromatic stimuli, of the order of 2–4 × threshold for J.C.B. and 3–6 × threshold for K.T.M., are sufficient to produce a smoothly moving percept and allow the velocity match to be made. At these luminance contrasts, although the 'capture' of colour by luminance contrast has evidently occurred, the unified stimulus is still perceived to move more slowly than its veridical velocity. The results of *Figure 2* show that increasing the luminance contrast produces an increase in the perceived drift rate of the stimulus until asymptotic and veridical values are obtained.

The interesting feature of these results is that luminance contrasts which are sufficient to make luminance-only gratings move at their veridical rate, become insufficient when presented in combination with colour contrast. The fine dashed line in the figure indicates the results for luminance-only gratings, and the results for the combined colour/luminance stimuli all fall at higher luminance contrasts.

The velocity matching function for each of the colour contrasts was fitted with a linear regression and extrapolated to the true drift rate (1.6 Hz) to give the luminance contrast required for veridical drift rate in the presence of each of the colour contrasts. The results are shown for each subject in *Figure 3*. The filled circles with the dashed lines indicate the luminance contrast required for the veridical drift rate of the luminance-only gratings, taken from the data of *Figure 1*. The open symbols indicate the luminance contrast required for the veridical drift rate in the presence of chromatic contrast. These results always lie above the dashed line confirming that, in the combined colour and luminance stimuli, greater luminance contrast is needed for a veridical drift rate than in the luminance-only stimuli. The results also show a trend whereby stimuli with higher colour contrasts require higher luminance contrasts for veridical motion. This relationship is relatively shallow, indicating that the negative contribution from colour contrast is weaker than the positive contribution from luminance contrast. At the highest colour contrasts, 10–30 × threshold of luminance contrast was needed to obtain a veridical drift rate.

Discussion

These results show that luminance contrast is not independent of colour contrast in its contribution to perceived velocity. Colour contrast reduces the effectiveness of luminance contrast in producing a perceived velocity at a veridical rate, and in general the higher the colour contrast the more luminance contrast is required to attain a veridical velocity. These results are compatible with previous observations that the addition of colour modulation to a luminance grating of fixed contrast reduces its perceived velocity[2] and are also likely to be related to the finding that the addition of colour contrast reduces the (luminance) motion after-effect[7].

Masking and velocity matching

It is worthwhile to recall that colour contrast has been found to produce a simultaneous threshold masking of luminance contrast[16]. Thus it is likely that the detection threshold of the luminance contrast in the drifting stimulus is increased in the presence of colour contrast. We have considered whether such a change in the luminance detection threshold might provide an explanation for the suprathreshold effects on perceived velocity that we have found.

We estimated the amount of the threshold masking of luminance contrast by colour for our stimulus conditions from the data of Switkes *et al.*[16]. The results are summarized in *Figure 4* (see the caption of *Figure 4* for further details). The right hand vertical axis relates to the filled circles and shows the increase in luminance threshold (expressed as multiples of the unmasked threshold), plotted as a function of the colour contrast (expressed as multiples of its threshold). The dashed line lying at unity indicates the contrast threshold for luminance stimuli with no chromatic mask. The results indicate that there is a small threshold masking of luminance contrast by colour contrast at the higher colour contrasts, first manifest > 10 × the colour contrast detection threshold.

The left hand vertical axis relates to the solid squares and shows the luminance contrast (in multiples of threshold) required to obtain a veridical drift rate of the stimulus, plotted as function of the colour contrast. These data have been taken from the results of *Figure 3*. The

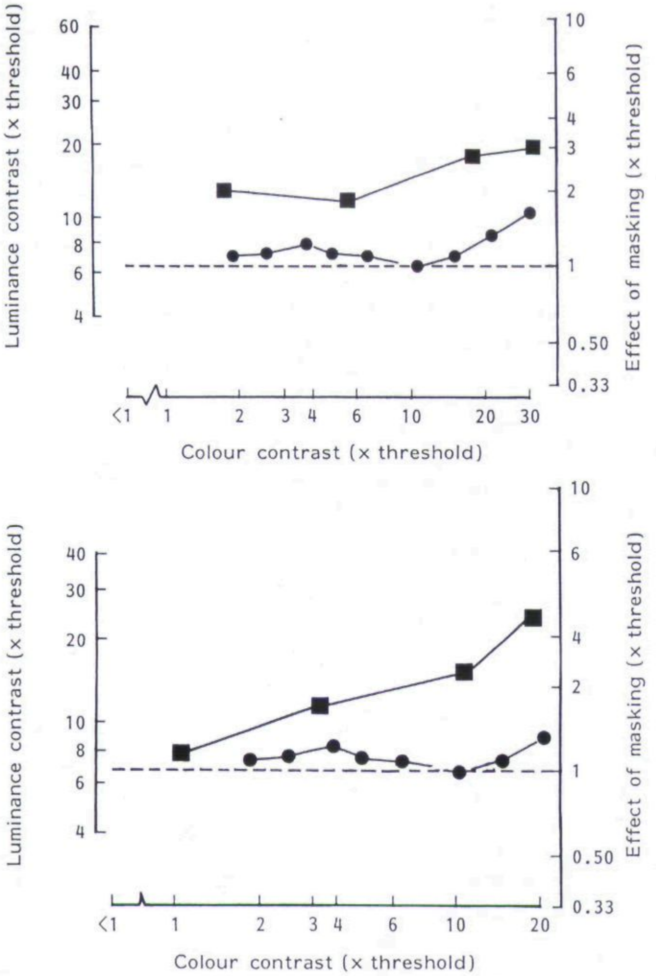

Figure 4 The solid squares relate to the left-hand axes and are taken from the data of *Figure 3*. The solid circles relate to the right-hand axes and the data are replotted from Switkes *et al.* (1988). This shows the elevation in luminance contrast threshold (in threshold multiples) in the presence of a chromatic mask. Data are the average of the results for stimuli of 0.5 and 2 c/deg (AB), whereas our stimulus is 1 c/deg. In the masking condition luminance contrast was produced by the addition of a yellow modulated stimulus. The common x axis is the chromatic contrast in threshold multiples. The dashed line indicates performance levels in the two tasks in the absence of colour contrast for luminance gratings

dashed line indicates the luminance contrast required for a veridical drift rate of luminance stimuli in the absence of colour contrast. A comparison of the circles and squares shows that the elevation of luminance contrast needed for a veridical drift rate in the presence of colour contrast is greater than the elevation of luminance threshold produced by chromatic masking (by ≈ 0.27–0.40 log units). The extent of this comparison is obviously limited by potential differences in the data sets arising from various factors such as subject differences, methodological and stimulus differences.

The results suggest that, in the presence of colour contrast, the function relating perceived velocity to luminance contrast can be translated along the luminance axis with no overall change in shape (compare the fine dashed line with the data in *Figure 2*). This is supported by the similarity of the slopes of the linear regressions for *Figures 1* and *2*; for J.C.B. the slope for the luminance-only stimuli is 0.043 compared with an average of 0.046 in the combined colour and luminance stimuli, and for K.T.M. these two are 0.045 and 0.049 respectively. At least some of this effect can be accounted for by the threshold chromatic masking of luminance contrast.

How might an increase in luminance contrast threshold in the presence of colour extend the dependence of perceived drift rate on luminance contrast? Models of velocity encoding propose that the independence of drift rate (or velocity) from luminance contrast is achieved by the comparison of the activities of different spatiotemporally tuned mechanisms, and hence the dependence of perceived drift rate on contrast indicates the detection of the stimulus by a single spatiotemporal mechanism[15,17]. If the luminance thresholds in these spatiotemporal mechanisms are raised by chromatic masking, a shift in the contrast dependence of drift rate to higher contrasts would be expected. This explanation implies that colour contrast has an input to the spatiotemporal mechanisms encoding the drift rate of luminance contrast.

There are two caveats in this possible explanation. First, the effect of colour contrast in reducing the contribution of luminance contrast to perceived motion is considerably greater than would be predicted from the change produced in luminance contrast threshold. This suggests that there could be a differential effect of colour contrast on the spatiotemporal mechanisms involved in the motion task. Second, the masking task is quite different in nature from the velocity matching task and so there is no obvious or direct link between the two. In the masking task the subject is required to make a discrimination between two suprathreshold stimuli that may be based on their local colour and luminance differences. Thus linking performance in the masking task to the velocity match depends upon the model of the masking mechanism that one adopts.

Motion capture?

Our results demonstrate that high luminance contrasts up to 10–30 × threshold are required to obtain a veridical velocity in chromatic stimuli. Thus we may discard a common assumption that it is simply the absence of isoluminance in the natural visual scene which is sufficient to explain the synchrony of its moving colour and luminance attributes[18]. On the contrary, it is likely that a significant proportion of the colour differences in a scene will fall below the required 10–30 × threshold of associated luminance contrast and therefore would not be expected to move at a veridical rate. Thus the question of why we fail to see discrepancies in the perceived velocities of the colour and luminance aspects of a moving object becomes more intriguing, and may point to a need to consider higher perceptual mechanisms in the motion capture phenomenon.

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