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Speed and the coherence of superimposed chromatic gratings

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ABSTRACT

On the basis of measurements of the perceived coherence of superimposed drifting gratings, Krauskopf and Farell (1990) proposed that motion is analysed independently in different chromatic channels. They found that two gratings appeared to slip if each modulated one of the two 'cardinal' color mechanisms S/(L + M) and L/(L + M). If the gratings were defined along intermediate color directions, observers reported a plaid, moving coherently. We hypothesised that slippage might occur in chromatic gratings if the motion signal from the S/(L + M) channel is weak and equivalent to a lower speed. We asked observers to judge coherence in two conditions. In one, S/(L + M) and L/(L + M) gratings were physically the same speed. In the other, the two gratings had perceptually matched speeds. We found that the relative incoherence of cardinal gratings is the same whether gratings are physically or perceptually matched in speed. Thus our hypothesis was firmly contradicted. In a control condition, observers were asked to judge the coherence of stationary gratings. Interestingly, the difference in judged coherence between cardinal and intermediate gratings remained as strong as it was when the gratings moved. Our results suggest a possible alternative interpretation of Krauskopf and Farell's result: the processes of object segregation may precede the analysis of the motion of chromatic gratings, and the same grouping signals may prompt object segregation in the stationary and moving cases.

1. Introduction

When two orthogonally oriented gratings move over one another, two percepts are possible. Either two separate gratings are seen to be slipping orthogonally over one another, or they appear to cohere in a plaid and move in a direction that is consistent with the "intersection of constraints" of the two component moving gratings (Adelson & Movshon, 1982; Wallach, 1935 translated by Wuerger, Shapley, & Rubin, 1996). The distinction seen in human phenomenology has also been observed in electrophysiological recordings from single units in macaque: whereas in the primary visual cortex, directionally-selective neurons respond to the motions of the component gratings, in area MT many neurons respond to the motion of the plaid (Movshon, Adelson, Gizzi, & Newsome, 1985).

The perceived coherence of two superimposed gratings depends on the similarity, in terms of contrast and spatial frequency, of the components: large differences in contrast and spatial frequency cause the component gratings to slip, and maximum coherence occurs when the component gratings have equal contrast and spatial frequency (Adelson & Movshon, 1982; Wallach, 1935 translated by Wuerger et al., 1996). In 1990, Krauskopf and Farell reported, intriguingly, that the coherence of the percept depended on the chromaticities of the component gratings; and it is with their study that the present experiments are concerned.

At a retinal level, human color vision is thought to rely on two 'cardinal' chromatic mechanisms. One takes input from the S-cones and compares it to combined input from the L and M cones (S/(L + M)), while the other compares inputs from the L and M cones (L/(L + M)). The MacLeod and Boynton (1979) chromaticity diagram represents colors in a physiologically relevant way: L/(L + M) is plotted along the abscissa, and S/(L + M) along the ordinate.

Results from both electrophysiology and psychophysics show that in some perceptual tasks the two cardinal chromatic mechanisms can act independently (Boynton & Kambe, 1980; Krauskopf, Williams, & Heeley, 1982; Stromeyer & Lee, 1988), but in many other tasks they interact (Boynton, Nagy, & Eskew, 1986; Danilova & Mollon, 2012; Flanagan, Cavanagh, & Favreau, 1990; Krauskopf, Williams, Mandler, & Brown, 1986; Krauskopf,

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Zaidi, & Mandler, 1986; Stromeyer et al., 1998; Webster & Mollon, 1991). Krauskopf and Farell (1990) provided a particularly strong demonstration of the independence of the cardinal chromatic mechanisms. If one of two orthogonally superimposed gratings was defined by chromatic modulation along one cardinal direction and the second by modulation along the other cardinal direction, then the gratings appeared to slip. If, however, the two gratings were defined by chromatic modulations along two orthogonal intermediate color directions, they appeared to move coherently as a plaid. Krauskopf and Farell's results were not caused by a mismatch between the superimposed gratings in perceived contrast: They fixed the contrast of one grating and varied the other in steps between threshold contrast and the maximum achievable, and found that there was no ratio of contrasts under which 'cardinal' gratings cohered. Krauskopf and Farell concluded from their results that motion is analysed separately within each cardinal mechanism.

Krauskopf, Wu, and Farell (1996) conducted a follow-up study that used perceived coherence as a way of defining the cardinal axes for individual observers, and to investigate further the stimulus parameters that led to perception of coherence. In the 1990 study, observers had been required to make a binary judgement of whether the stimulus appeared to be coherent or not. In 1996, Krauskopf and his colleagues used a 2-interval procedure, in which observers were required to choose which of two stimuli appeared more coherent. The result of this was a conclusion more nuanced than that from the first study: Even intermediately modulated chromatic gratings were minimally coherent if the two directions of chromatic modulation were orthogonal. However, coherence was still much lower for cardinal gratings than for intermediate gratings. Cropper, Mullen, and Badcock (1996), using as a dependent measure the perceived direction of "the most salient motion of the pattern at the end of the presentation interval", confirmed the lack of coherence found by Krauskopf and Farell (1990) when the component gratings fell on opposite cardinal axes and when the geometrical angle between the components was 90 deg; but coherence was observed when the geometrical angle between the components was reduced.

Krauskopf and Farell's (1990) main conclusion, that motion is analysed separately in the two cardinal chromatic mechanisms, is in contradiction to the view that motion of isoluminant stimuli is analysed in a single 'colorblind' system. For example, Lu, Lesmes, and Sperling (1999), on the basis that isoluminant motion has a low-pass temporal tuning function, fails a pedestal test, and is perceived equally well interocularly, concluded that the system for chromatic motion is third-order: Motion is extracted at a level where form, color, and depth are all accessible to the same feature-tracking system.

Because Krauskopf and Farell's conclusions seem to contradict results like those of Lu et al. (1999), they deserve closer scrutiny. One alternative account of Krauskopf and Farell's finding is that the cardinal gratings failed to cohere because they generate mismatched velocity signals. If the internally represented velocity of S(L + M) gratings is lower than that of L/(L + M) gratings, it could be the disparity in velocity signals, rather than the fact that speed is analysed in different channels *per se*, that is causing the superimposed gratings to appear to slip. There is good reason to suppose that there could be a disparity in the perceived speeds of gratings that modulate S/(L + M) and gratings that modulate L/(L + M). Nguyen-Tri and Faubert (2002) have found that at isoluminance, the perceived speed of moving S-cone isolating stimuli is less than half of that of other chromatic stimuli.

In Experiment 1 we sought to replicate Krauskopf and Farell's (1990) findings. In Experiment 2a we tested our hypothesis that differences in velocity signals are driving the difference between chromatic conditions that Krauskopf and Farell observed. We measured the perceived coherence of orthogonally superimposed isoluminant gratings in two speed conditions. In one, the S/(L + M) and L/(L + M) gratings were physically matched in speed, in the other they were perceptually matched in speed using the results of an asymmetric speed-matching task. In Experiment 2b we asked observers who had already taken part in Experiment 2a to judge the coherence of *stationary* plaids.

2. Methods

All gratings presented in Experiments 1 and 2 were 1 cycle per degree of visual angle (c.p.d) and oriented at 45° to the vertical. Each pair of gratings to be superimposed was made isoluminant for each observer using the results of flicker photometry, where observers perceptually matched the intensities of the monitor's three primaries.

Plaid stimuli were created by temporal dithering: Orthogonal isoluminant component gratings were presented on alternate frames (Fig. 1(b)). The luminance of the plaids was approximately 27 cd m^{-2}, but varied slightly between observers depending on their flicker-photometric settings. Plaids were presented in a circular aperture of diameter 7° on a grey surround. The surround was metameric with equal energy white, and isoluminant (individually for each observer) with the plaids.

Stimuli were presented on a GDM F400T9 CRT monitor (Sony, Tokyo, Japan) running at 120 Hz. Gamma correction was achieved using a CS-100 luminance meter (Konica Minolta, Tokyo, Japan), and the color calibration was achieved using a Spectrascan PR650 spectroradiometer (Photo Research Inc, Chatsworth, CA). Experiments were run in Matlab R2007b (The MathWorks, Natick, MA), and stimuli created and presented using a vsg2/5 graphics card (Cambridge Research Systems, Rochester, UK). Responses were gathered using a CT3 response box (Cambridge Research Systems).

All participants gave written, informed consent before taking part in the experiments. The work was carried out in accordance with the Code of Ethics of the World Medical Association.

3. Experiment 1. Dependence of coherence on grating chromaticities

Experiment 1 aimed to replicate the findings of Krauskopf and Farell (1990), and so followed their methods closely.

3.1. Methods

On each trial two superimposed sinusoidal gratings were presented for 1 s, each drifting at 1 deg/s. The gratings were oriented orthogonally so that the sinusoidal modulations were along the positive and negative diagonals. The directions of motion were along the same axes tending upwards (see Fig. 1(b) for a schematic). A blank grey screen of luminance 27 cd m^{-2} was displayed until a response from the observer was received, which triggered the next trial.

Over 100 trials, there were 25 presentations of each of four chromatic conditions, in a random order. In one condition (the 'cardinal' condition) one grating was defined by a modulation in S/(L + M) only, and the other was defined by a modulation in L/(L + M) only. In the other three conditions (intermediate conditions 1–3), the two gratings were defined by two orthogonal chromatic modulations, but along intermediate axes rather than along the cardinal axes of the MacLeod and Boynton (1979) chromaticity diagram. Fig. 1(a) shows the chromaticities that defined the gratings in each of the four chromatic conditions, which were constrained by the monitor's gamut. The Michelson contrast of the L/(L + M) grating was 0.045, and that of the S/(L + M) grating was 0.4.