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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.

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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.
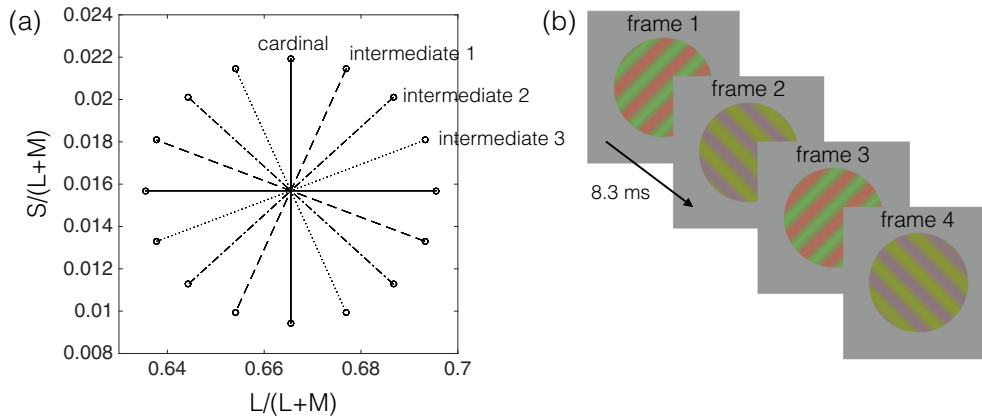
Fig. 1. (a) Stimulus chromaticities plotted in the MacLeod and Boynton (1979) chromaticity diagram. Each line shows the locus of chromaticities that defined an isoluminant grating in the experiment. There were four conditions, and in each condition two gratings were presented (oriented orthogonally) that were defined along orthogonal chromatic axes. The chromaticities of the two gratings that were presented in the 'cardinal' condition are shown by the solid black lines, and the chromaticities of the gratings shown in intermediate conditions 1, 2 and 3 are shown by the dashed, dot-dashed and dotted lines, respectively. (b) Schematic of the first four frames of the stimulus. Gratings defined by orthogonal chromatic loci were presented on alternate frames. Between subsequent presentations of a chromatic grating there was a phase change (exaggerated in the illustration) to cause the grating to drift. On each trial the stimulus train continued for 120 frames.

On each trial the observer was required to indicate whether the gratings cohered or slipped. He or she was instructed that the stimulus should be judged coherent if it appeared to move together as one pattern, and that it should be judged to slip if two separate patterns appeared to move over one another. Percepts were reported by means of a button press.

Nine observers took part in Experiment 1. All had normal color vision, assessed by the Ishihara Plates. Six were naïve to the purposes of the experiment.
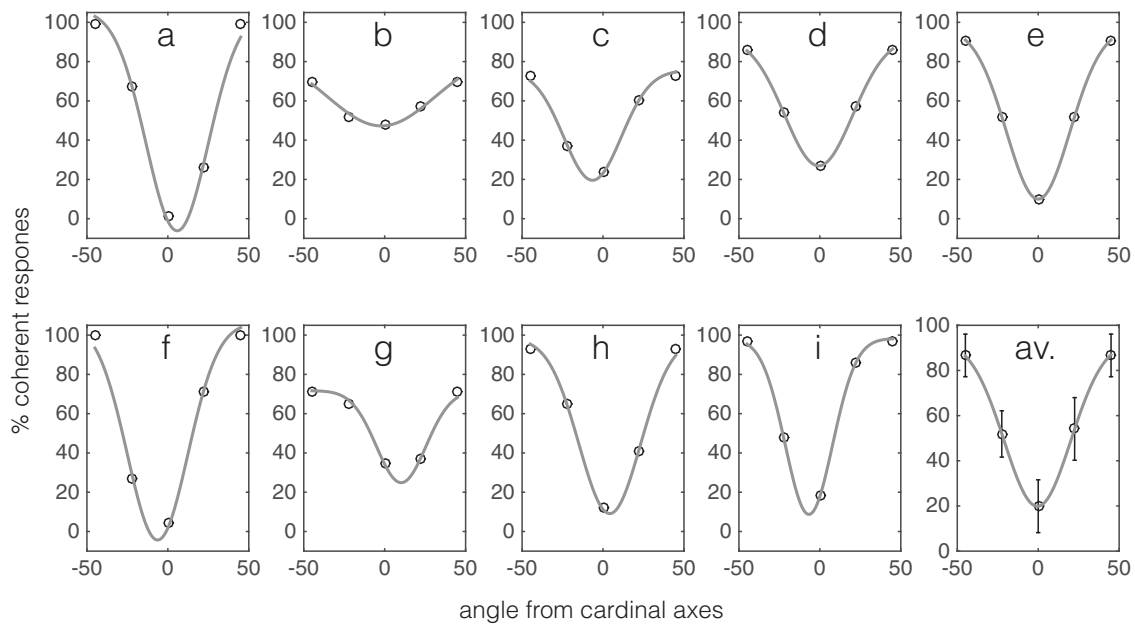
3.2. Results

Fig. 2 shows the results of Experiment 1. All observers gave fewer coherent responses for gratings that were defined along

the two cardinal axes than for gratings that were defined along intermediate axes. On average, about 20% of trials were judged coherent for cardinal gratings, and over 80% for intermediate condition 2 (lower right panel). We thus replicated Krauskopf and Farell's (1990) result that superimposed gratings defined along the cardinal axes of the MacLeod and Boynton (1979) chromaticity diagram are judged to be less coherent than superimposed gratings defined along orthogonal intermediate axes.

4. Experiment 2a. Dependence of coherence on perceived speed

Experiment 2a had two parts: in the first part observers matched the perceived speed of a grating defined by a modulation in $S/(L + M)$ to the perceived speed of a grating defined by a

Fig. 2. Results of Experiment 1. In each panel, the x-axis represents the angle of the chromatic axis from the cardinal axis. The cardinal condition has an angle of 0, intermediate conditions 1 and 3 have an angle of 22.5° but in opposite directions (see Fig. 1(a)), and intermediate condition 2 has an angle of 45°. In each panel, the data point plotted at −45° and +45° results from intermediate condition 2: this data point is plotted twice. The y-axis represents the percentage of responses that were judged coherent. Results from 9 individual observers are plotted in panels a–i, and the group average with 95% confidence intervals is plotted in the lower right panel. Fitted curves are inverted Gaussians.

modulation in L/(L + M). Physically, the speed of the S/(L + M) grating varied while the speed of the L/(L + M) grating was fixed. In the second part, speed-matched gratings were orthogonally superimposed, and observers had to judge their coherence.

4.1. Methods

The speed-matching task was two-interval. In one interval lasting 1 s, a grating defined by a modulation in L/(L + M) was presented, moving at 1 deg/s. In the other interval (also 1 s), a grating defined by a modulation in S/(L + M) was presented, that had a speed specified on each trial by one of two randomly interleaved ZEST staircases (King-Smith, Grigsby, Vingrys, Benes, & Supowit, 1994; Watson & Pelli, 1983) with a starting speed of 1 deg/s. The chromaticities of both gratings were the same as those used in the 'cardinal' condition of Experiment 1 (Fig. 1(a)). The starting phase of each grating was randomised. The two gratings were oriented orthogonally along the positive and negative diagonals, but which grating was presented on which diagonal was decided randomly on each trial. There was an inter-stimulus interval of 250 ms, where a blank grey field of luminance 27 cd m^{-2} was displayed. After a response was received, there was a similar interval of 500 ms before the start of the next trial.

On each trial, the observer's task was to decide in which interval the grating moved faster, and to respond by pressing a button. There were 3 blocks of 100 trials: each staircase terminated after 50 trials.

The point of subjective equality where the speed of the S/(L + M) grating appeared to match that of the L/(L + M) grating was found by averaging the final threshold estimates of the six ZEST staircases, which each had a threshold criterion of 0.5.

In the second part of Experiment 2a, observers had to judge the perceived coherence of orthogonally superimposed drifting chromatic gratings when the gratings were either physically matched in speed or perceptually matched in speed. The methods were the same as those of Experiment 1, except for differences in the speeds of the superimposed gratings.

There were 4 blocks of 120 trials. In each block there were 4 chromatic conditions (as in Experiment 1; see Fig. 1(a)) and 2 speed conditions: each condition was presented on 60 trials. In one speed condition the superimposed drifting gratings were physically matched in speed, and in the other speed condition the speeds were defined by the points of subjective equality measured in the speed-matching task.

On trials where the gratings were physically matched in speed, they all drifted at 1 deg/s. For the cardinal condition, on trials where the speeds of the gratings were perceptually matched, the L/(L + M) grating drifted at 1 deg/s, and the S/(L + M) grating drifted at a speed set at the point of subjective equality measured in the speed-matching task. For the other chromatic conditions, one grating, randomly chosen, had a speed of 1 deg/s, and the other had a speed the same as the S/(L + M) grating in the cardinal condition.

13 observers took part in Experiment 2a. All had normal color vision assessed using the Ishihara Plates. 10 observers were naïve to the purposes of the experiment, and these 10 observers had not previously taken part in Experiment 1.

4.2. Results

On average, observers perceived equal speed for the two cardinal gratings when the S/(L + M) grating was moving at 0.92 times the speed of the L/(L + M) grating, and there were large individual differences (SD 0.48). The average observer thus perceived S/(L + M) gratings to be moving *faster* than L/(L + M) gratings when both were moving at physically the same speed. This is in the opposite direction to the results of Nguyen-Tri and Faubert (2002).

Fig. 3(a) and (b) shows the results of Experiment 2a for cardinal gratings. If perceived slippage in the cardinal condition is caused by the two gratings generating mismatched velocity signals, then perceived coherence should increase in the condition where the gratings are matched in perceived speed. In Fig. 3(a) we should therefore expect the data points to lie above the dashed line. There is no such consistent pattern in the data, and mean perceived coherence is almost identical in the two conditions (Fig. 3(b)). There are large individual differences in the proportion of superimposed gratings judged coherent – one observer judged the stimuli to be almost 100% coherent, but that observer judged all stimuli in all chromatic conditions to be 100% coherent. The mean perceived coherence in both speed conditions is 26% for the cardinal chromatic condition – similar to the proportion judged coherent in Experiment 1 (see Fig. 2 lower right panel).

Fig. 3(c) shows the results of all the chromatic conditions. For the non-cardinal superimposed gratings, both gratings drifted at the same physical speed (black line) or one randomly chosen grating drifted at the speed of the S/(L + M) grating in the cardinal condition (grey line). In all chromatic conditions the speed manipulation made no difference to the perceived coherence of the stimulus.

4.3. Interim discussion

We found that a mismatch in velocity signals arising from the S/(L + M) gratings and the L/(L + M) gratings is not responsible for the low perceived coherence that is observed in the cardinal condition: When the speeds of the two gratings are matched perceptually, perceived coherence does not change.

While conducting Experiment 2a we noticed that the stimulus cues that could be used to judge coherence did not necessarily relate to motion. Specifically, we noticed that we judged stimuli to be coherent if they contained "blob" features at points of intersection in the superimposed pattern (see Discussion for speculation about the origin of these). So to determine whether motion signals are in fact critical for an explanation of Krauskopf and Farell's result, we presented stationary superimposed gratings to the observers who had taken part in Experiment 2a; and we asked these observers to make judgements of "coherence" as before.

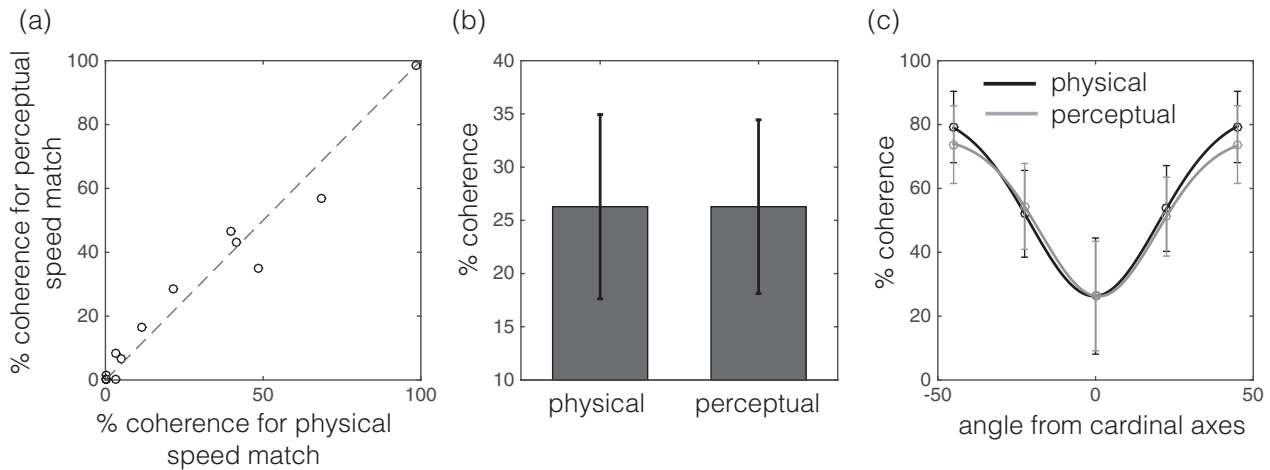## 5. Experiment 2b. Perceived coherence of stationary gratings

5.1. Methods

The methods of Experiment 2b were the same as those of Experiments 1 and 2a, except that the superimposed gratings did not drift. The 13 observers who took part in Experiment 2b also took part in Experiment 2a. Observers were instructed to judge the coherence of the stationary gratings using the same method as they used to judge the coherence of the moving gratings in Experiment 2a. Note that in this condition observers were not asked to make judgements about motion but to judge whether the component gratings cohered (to form a single object).
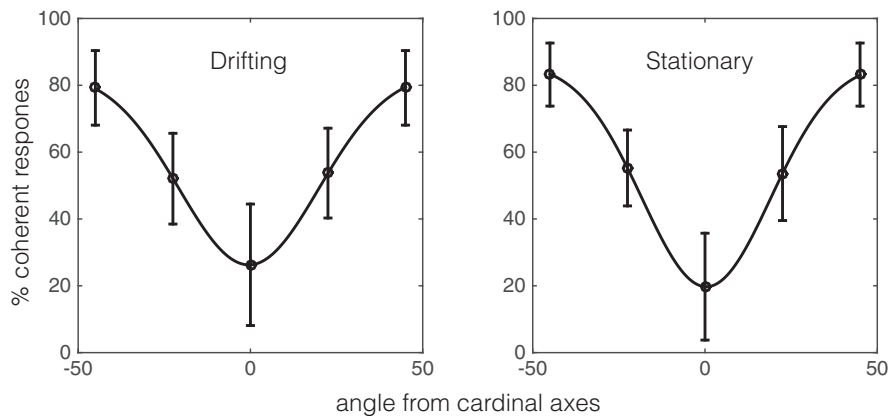
5.2. Results

Fig. 4 shows group mean coherence judgments for drifting and stationary superimposed gratings. The results for drifting gratings are those for the physically speed matched condition of Experiment 2a. Interestingly, the data show that perceived coherence (in trained observers) is judged in the same way for stationary gratings as it is for drifting gratings.

For both stationary and drifting gratings, perceived coherence is minimal for gratings defined along the cardinal axes of the

Fig. 3. Results of Experiment 2a. (a) Perceived coherence of cardinal superimposed gratings in the two speed conditions. The dashed line is the locus of equality between the two conditions. (b) Mean perceived coherence for cardinal superimposed gratings in the two speed conditions. Error bars are standard errors of the mean. (c) Perceived coherence in the four chromatic conditions (Fig. 1(a)) for superimposed gratings that drift with the same physical speed (black line) or where one grating drifts at a speed determined by the perceptual match between a drifting S/(L + M) grating and a drifting L/(L + M) grating (grey line). Error bars are 95% confidence intervals.

Fig. 4. Results of Experiment 2b. In the left panel are plotted results from Experiment 2a for the condition where the drifting gratings had physically matched speeds. The right panel shows judged coherences for superimposed gratings that were stationary. Error bars are 95% confidence intervals on the mean.

MacLeod and Boynton (1979) chromaticity diagram, and maximal for diagonal chromatic axes. A repeated measures ANOVA confirmed that there was no significant difference in reported coherence between the drifting and stationary conditions ($F_{1,96} = 0.03$, $p = 0.85$).

6. Discussion

In experiment 1 we confirmed the striking finding of Krauskopf and Farell that superimposed chromatic gratings fail to cohere when the two isoluminant components lie along different axes of the MacLeod and Boynton (1979) chromaticity diagram. In experiment 2a we asked whether this result arises from a mismatch in velocity signals within the S/(L + M) and L/(L + M) channels. In fact, when gratings were equated for apparent speed, the results were almost identical to those obtained without such equation. Our primary hypothesis was thus disconfirmed.

Experiment 2b generated a curious result. We asked our observers, trained to report coherence or incoherence in moving superimposed chromatic gratings, to judge the coherence of stationary chromatic superimposed gratings on the same basis as they had judged the moving gratings. For these stationary plaids observers were again least likely to perceive a single coherent object when the component gratings were defined along the cardinal color axes.

What could explain the results of Experiments 2b? Could there be a common cue that observers use to make their judgements in both conditions? We discuss three alternative, but not mutually exclusive, possibilities in turn.

1. Transparency. For two gratings to appear to slip over one another, the grating in the foreground at each moment must appear to have a degree of transparency (Stoner, Albright, & Ramachandran, 1990). There is evidence that transparency perception is possible for uniform stationary chromatic stimuli arranged in a way to make a transparency interpretation plausible (Brenner & Cornelissen, 1991; Ekroll, 2005). For transparency to explain our results, the plausibility of transparency as an interpretation of superimposed gratings would have to depend on the chromatic condition.

2. Rivalry. When two stationary gratings are orthogonally superimposed either they appear to form a stable plaid, or they appear to alternate (Breese, 1899; Campbell & Howell, 1972). The latter percept has been named monocular rivalry (Breese, 1899) and is particularly strong for superimposed chromatic gratings (Campbell & Howell, 1972; Rauschecker, Campbell, & Atkinson, 1973). It is possible that pairs of superimposed cardinal gratings show greater monocular rivalry than pairs of superimposed intermediate gratings owing to competition between the two cardinal color mechanisms. However, Thomas (2004)

found in two out of his four participants that this is not the case and his result is clearly discouraging for any potential account of our results based on monocular rivalry.

3. Nodes. In plaid stimuli, at locations where the extrema of the component gratings coincide, there are visible "nodes" or "blobs" when the component sinusoids constructively or destructively interfere (Adelson & Movshon, 1982). In a moving plaid, the direction of the motion of the nodes is the direction of the intersection of constraints. Cropper et al. (1996) showed that for Type II chromatic plaids – where the direction of motion of the intersection of constraints differs from the vector sum of the motions of the two component gratings (Ferrera & Wilson, 1987) – the probability of a coherent percept increases as the angle between the motion directions of the component gratings reduces. Cropper et al. (1996) attributed this finding to the increased salience of nodes as the orientations of the component gratings converge. As observers ourselves in the present experiments, we observed that the salience of nodes depended on the chromatic condition, and that the prominence of the nodes was associated with our coherence judgements. There are two possible sources of the nodes in chromatic plaids: saturation summation and luminance summation. In the former case, saturation signals would sum for pairs of intermediately chromatically tuned gratings when cardinal mechanisms are driven in the same direction. Saturation signals would not sum for pairs of cardinal gratings because summation would not be possible across the two cardinal mechanisms. The presence of luminance nodes in plaids composed of superimposed luminance gratings has been well studied (e.g. Adelson and Movshon (1982), Burke, Alais, and Wenderoth (1994), Ferrera and Wilson (1991), Wenderoth, Alais, Burke, and van der Zwan (1994)). Our stimuli were made isoluminant for each observer using flicker photometry. Nevertheless there is evidence that "equiluminant" $L/(L + M)$ stimuli do not isolate chromatic channels, but also modulate some luminance channels (Ingling & Martinez Uriegas, 1983; Lee, Martin, & Valberg, 1989a, 1989b; Lennie & Movshon, 2005). Luminance nodes could therefore appear in any condition where the two superimposed gratings each contained some modulation in $L/(L + M)$, as occurred in the 3 intermediate conditions. However, S-cones make minimal or zero contribution to luminance and so we should expect that nodes would be absent in the cardinal condition when one grating is defined along the $S/(L + M)$ axis.

7. Conclusions

The results of experiment 2b suggest an alternative interpretation of Krauskopf and Farell's (1990) results. It may be that the processes of object segregation precede the analysis of motion for an isoluminant plaid, and that a common feature, such as the superposition of saturation or luminance signals at nodes, underlies the formation of a grouped object in both static and moving cases.

Krauskopf and Farell (1990) favoured the alternative interpretation, that motion is analysed independently in the two cardinal chromatic channels. This hypothesis is still viable if similar segregation rules are also used in a parallel analysis of objects. It is possible that the same Gestalt grouping principles apply in the two domains, and that the similarity of results in experiments 2a and 2b is fortuitous.

Theories of the present result and of similar phenomena fall into two generic classes: (i) Those that suppose that special behaviors emerge when the two component modulations fall on cardinal axes and (ii) those that suppose that special behaviors emerge when one of the modulations is confined to the tritan axis of color space. The hypothesis with which we began this work would fall

into the latter class, as would an explanation in terms of the absence of S-cone input to 'luminance' channels of the visual system. Theories of classes (i) and (ii) make different predictions for the case where one grating remains on the tritan line while the second is not at 90° to it in the MacLeod and Boynton (1979) chromaticity diagram, but rather is at some smaller angle. Theories of type (ii) predict that coherence will still fail. But it will not fail in the mirror-image situation when one grating lies on the L/M axis and the chromatic direction of the other is varied.

Acknowledgments

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