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Colour contrast influences perceived shape in combined shading and texture patterns

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Abstract—The ‘colour-shading effect’ describes the phenomenon whereby a chromatic pattern influences perceived shape-from-shading in a luminance pattern. Specifically, the depth corrugations perceived in sinusoidal luminance gratings can be enhanced by spatially non-aligned, and suppressed by spatially aligned sinusoidal chromatic gratings. Here we examine whether colour contrast can influence perceived shape in patterns that combine shape-from-shading with shape-from-texture. Stimuli consisted of sinusoidal modulations of texture (defined by orientation), luminance and colour. When the texture and luminance modulations were suitably combined, one obtained a vivid impression of a corrugated depth surface. The addition of a colour grating to the texture-luminance combination was found to enhance the impression of depth when out-of-phase with the luminance modulation, and suppress the impression of depth when in-phase with the luminance modulation. The degree of depth enhancement and depth suppression was approximately constant across texture amplitude when measured linearly. In the absence of the luminance grating however, the colour grating had no phase-dependent affect on perceived depth. These results show that colour contrast modulates the contribution of shading to perceived shape in combined shading and texture patterns.

Keywords: Colour; texture; shape-from-shading.

INTRODUCTION

The role that colour vision plays in the analysis of form is of considerable interest to vision scientists (e.g. see review by Regan, 2000). A popular technique for studying this topic is to measure performance on a given form task using isoluminant (colour-only) and isochromatic (luminance-only) stimuli. However, much can be learnt about the role of colour vision in form perception by studying how colour and

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luminance interact in stimuli that emulate the spatio-temporal relationships between colour and luminance found in the natural visual world (Kingdom, 2003).

The 'colour-shading effect' (Kingdom, 2003; Kingdom *et al.*, 2005) is a recent example of this approach. When a chromatic grating is added to a differently-oriented luminance grating, one obtains an impression of a corrugated surface – an instance of 'shape-from-shading'. We term this 'depth-enhancement'. However, when a second chromatic grating of the same orientation and spatial phase as the luminance grating is added, the impression of depth is reduced or eliminated. We term this 'depth-suppression'. These observations show that shape-from-shading, hitherto studied primarily in the achromatic domain (Lehky and Sejnowski, 1988; Ramachandran, 1988; Attick *et al.*, 1996; Sun and Perona, 1997), can be profoundly influenced by colour contrast. Kingdom (2003) argued that the depth-enhancing and depth-suppressing capabilities of colour contrast observed in colour/luminance patterns reveal that the visual system has certain built-in assumptions. These are: (1) chromatic variations, and those luminance variations that are spatially aligned with them, arise from changes in surface reflectance; (2) pure, or near-pure luminance variations, arise from spatially non-uniform illumination, such as shading and shadows. Although the physical relationships that underpin these assumptions have been appreciated by vision scientists for some time (Rubin and Richards, 1982; Cavanagh, 1991; Mullen and Kingdom, 1991; Olmos and Kingdom, 2004), the colour-shading effect is the first evidence that these assumptions are built into the fabric of the human visual system.

In natural scenes there are often multiple cues to surface shape. Does the modulatory influence of colour contrast on the perception of surface shape occur with cues other than shading, such as texture, and does colour contrast influence the contribution of shading to surface curvature when it is present alongside other cues? It is possible that the influence of colour contrast on shape-from-shading is reduced, or even eliminated, when surface information other than colour is present, because in such circumstances the surface-*versus*-illumination interpretative role of colour contrast becomes redundant. The aim of the present study is to determine whether colour contrast influences perceived shape in patterns that combine shape-from-shading with shape-from-texture.

Orientation-defined textures are a powerful perceptual cue to surface shape (Li and Zaidi, 2000), and this is to be expected given how informative are variations in local orientation for surface shape analysis (Stevens, 1988; Knill, 2001). Moreover, orientation-defined textures have been shown to combine synergistically with shading to create strong impressions of depth (Mamassian and Landy, 2001). For these reasons we have chosen orientation-defined textures as our second cue to surface shape.

In our two previous studies of the colour-shading effect (Kingdom, 2003; Kingdom *et al.*, 2005), subjects adjusted the amplitude of a random-element, disparity-modulated stereo-grating to match the perceived depth of the corrugations in the plaid patterns. One criticism of this method is that binocular viewing the patterns may have obscured subtle depth differences because stereo-vision would signal 'flat'. For this reason we have also measured the perceived depth in our test stimuli using a new method, in which subjects viewed the stimuli monocularly and adjusted the height of a bar to indicate the amount of depth they perceived. Details of these procedures are provided below.

METHODS

Subjects

The four authors were test subjects. All had normal or corrected-to-normal visual acuity and normal colour vision. For the stereo-matching procedure, AY, FK and KW were employed. For the bar-adjustment procedure, GM, AY and KW were employed.

Stimuli

Generation and display. The stimuli were generated by a VSG2/5 graphics card (Cambridge Research Systems) and displayed on a Sony Trinitron F500 flat-screen monitor. The R (red), G (green) and B (blue) gun outputs of the monitor were gamma-corrected after calibration with an Optical photometer (Cambridge Research Systems). The spectral emission functions of the R, G and B phosphors were measured using a PR 640 spectral radiometer (Photo Research), with the monitor screen filled with red, green or blue at maximum luminance. The CIE coordinates of the monitors' phosphors were R: $x = 0.624$, $y = 0.341$; G: $x = 0.293$, $y = 0.609$; B: $x = 0.148$, $y = 0.075$.

Test stimuli. Example stimuli are shown in Fig. 1. The stimuli were constructed from three types of sinusoidally-modulated gratings: an orientation-modulated (OM) texture grating, a luminance modulated (LM) grating and a colour modulated (HM) grating (H stands for hue; we prefer this to CM, which is widely used to denote 'contrast-modulated'). All grating components had a spatial frequency of 0.75 cpd and an orientation of $-45°$ (left-oblique). The stimuli were presented in a circular, hard-edged window of diameter 4.5 deg. The OM and LM gratings were 'black-white', and were produced by modulating all three RGB phosphors in phase. The OM and LM gratings were presented together on one page of video memory, the HM on another. The two video pages were alternated at the monitor's frame-rate of 180 Hz, and thus the stimuli were refreshed at 90 Hz.

The OM grating comprised 600 Gabor patches with luminance spatial frequency 8.0 cpd, bandwidth at half-height of 1 octave, phase 90 deg (making them odd-symmetric, and hence d.c. balanced) and contrast 25%. The Gabors were randomly

Figure 1. (See colour plate VI) Example stimuli. Left hand panels = zero texture amplitude; right hand panels = 45 deg texture amplitude. Top pair = no colour conditions; middle pair = colour in-phase conditions; bottom pair = colour out-of-phase conditions.

positioned with the constraint that no two Gabors could be less than 2 standard deviations apart. The orientation of the Gabors was modulated sinusoidally around a mean orientation of 45 deg (right-oblique) and in the direction of 45 deg, producing texture bars at −45 deg (left-oblique). The phase of orientation modulation was randomized on each trial. The amplitude of orientation modulation determined by how much the orientation of the Gabors changed throughout one cycle of orientation modulation, and this was an independent variable with values 0.0, 5.63, 11.25, 22.5 and 45 deg. Examples of the 0 deg (left column) and 45 deg (right column) amplitude conditions are shown in Fig. 1.

The LM grating was combined with the OM grating multiplicatively. Multiplying the OM by the LM grating simulated real shading, which changes the average luminance but not contrast of local luminance variations. The phase of the LM grating was always set to 0 deg with respect to the orientation grating, and as can be seen in Fig. 1b, this phase relationship produced an impression of a corrugated surface illuminated from above-right. Note that with the OM grating, the d.c. orientations (45 deg) lie at the apparent peaks and troughs of the depth corrugation. The contrast of the LM grating was an independent variable, and values of 0.0, 0.037, 0.075, 0.15 and 0.3 were employed.

The HM grating was 'red-green', and was designed to isolate the post-receptoral chromatic mechanism that differences the L (long-wavelength-sensitive) and M (middle-wavelength-sensitive) cones. However, this choice of HM grating was arbitrary. Kingdom *et al.* (2005) showed that the colour direction of both the depth-enhancing and depth-suppressing chromatic gratings in the colour-shading effect was unimportant: it was their colour *contrast* that mattered. For this reason the details of the generation of the HM grating will not be given here, but the interested reader can consult the aforementioned article. The HM grating was fixed throughout at a (relatively high) L-M cone contrast of 0.08. There were three conditions: no colour grating, colour in-phase, and colour out-of-phase, as illustrated in Fig. 1, top to bottom respectively. For the in-phase condition (Figs 1c, d), the HM grating was added in phase to the LM grating, but with the polarity (0 or 180 deg) randomised, producing either a 'bright-red/dark-green', or 'dark-red/bright-green' grating. For the out-of-phase condition (Figs 1e, f), the HM grating was randomly allocated either 90 or 270 deg phase with respect to the LM grating.

Match stimuli. Two methods were used to estimate the apparent depth of the corrugations. The first method employed a random-Gabor stereo-grating with left-oblique corrugations of the same spatial frequency and orientation as the test stimuli. The matching stereo-pairs were positioned below the test stimuli on either side of the centre of the monitor screen. Stereo-fusion was achieved by viewing the display through a modified 8-mirror Wheatstone stereoscope. Viewing distance along the light path through the stereoscope was 105 cm. The details of the construction of the stereo-grating have been given elsewhere (Kingdom *et al.*, 2005) and will not be repeated here.

The second method used to estimate the perceived depth of the corrugations employed a vertical bar positioned below the test stimulus. The bar was 2 deg in height by 12 min in width, and was a shade of grey 0.12 in contrast darker than the background. The bar could be 'filled' with a shade of grey of 0.44 in contrast up to a height chosen by the subject. Viewing distance was also 105 cm.

Procedures

Isoluminance setting. Although our stimuli were not isoluminant, we wanted to minimize the likelihood that our HM grating introduced a luminance component to the stimulus. To this end we used an HM grating that when presented on its own was isoluminant according to the criterion of minimum perceived motion. To produce such a grating, we set an HM grating with an L-M cone contrast of 0.025 to drift at about 1.0 Hz. Subjects pressed a key on the CB3 response box (Cambridge Research Systems) to add or subtract an equal amount to both the L and -M cone contrasts until perceived motion was at a minimum. The resulting ratio of (absolute) L to M cone contrast weightings necessary to make the HM grating isoluminant was for GM 1.1, AY 1.67, KW 1.14 and FK 1.78.

Matching perceived depth using the adjustable stereo-grating. Subjects used the keys on the response box to adjust the amplitude of the depth corrugations in the stereo-grating until they matched the apparent depth of the corrugations in the test stimulus. There was no time limit. Subjects were encouraged to let their eyes roam freely over the stimuli to avoid any fading from prolonged fixation. During each session all conditions were presented in random order, and for all subjects except KW there were eight repeat sessions and therefore eight measurements per condition. For KW there were between four and twelve sessions/repeat measures, as her data formed part of a series of pilot experiments which explored the parameter space of the stimuli.

Matching perceived depth using the adjustable bar. Subjects used the keys on the response box to adjust the height of the bar to match the perceived depth of the corrugation in the test stimulus. No instructions were given as to which parts of the stimulus should be attended; subjects were simply told to set the bar height to indicate how much the bars 'stood out'. The whole display was viewed monocularly by the dominant eye, with the non-dominant eye covered by a patch. For all subjects there were eight sessions/repeat measures using this method.

RESULTS

To repeat: there were three colour conditions (no-colour, colour in-phase, colour out-of-phase), five texture amplitudes (0.0, 5.63, 11.25, 22.5 and 45 deg) and five shading contrasts (0.0, 0.037, 0.075, 0.15 and 0.3), making a total of $3 \times 5 \times 5 = 75$ conditions. Figures 2 and 3 show the mean settings for the adjustable stereo-grating and adjustable bar methods respectively, with the no-colour, in-phase and out-of-phase conditions shown in separate graphs. In all graphs, the magnitude of

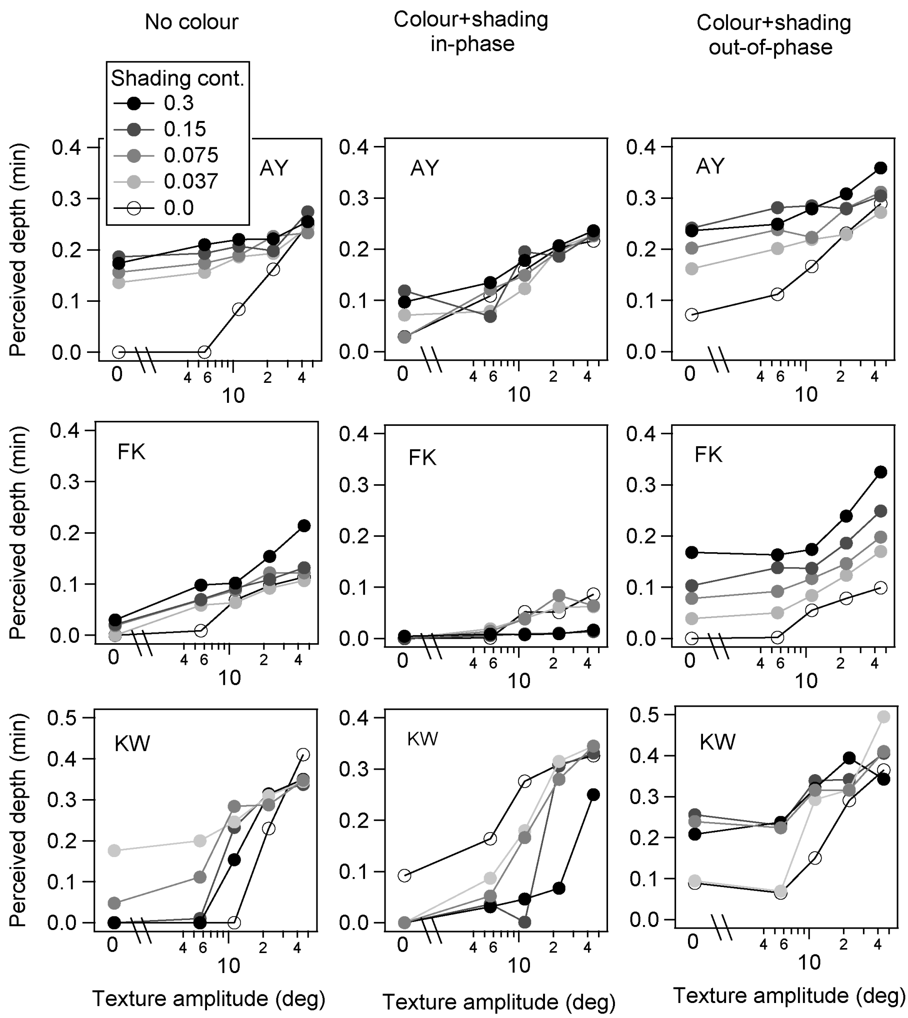

Figure 2. Results obtained using the stereo-grating matching method. In each graph perceived depth is plotted against the amplitude of texture modulation. Symbols with different shades of grey are for different luminance contrasts of the ‘shading’ grating. Left column = no-colour condition, middle column = colour in-phase condition, right column = colour out-of-phase condition. Error bars have been omitted to avoid cluttering.

perceived depth is plotted against texture amplitude, with separate plots for each shading contrast.

First note that in general an increase in either texture amplitude or shading contrast increased perceived depth. The effects of shading contrast are, however, largely absent in the in-phase conditions; this is most likely a floor effect resulting from the influence of in-phase colour contrast, which appears to reduce perceived depth to such an extent that little room is left for the effects of shading contrast. The effects of shading contrast are also anomalous in KW's no-colour condition, where, if anything, an increase in shading contrast reduced perceived depth, a result for which we have no explanation. KW's results are in general more erratic than the

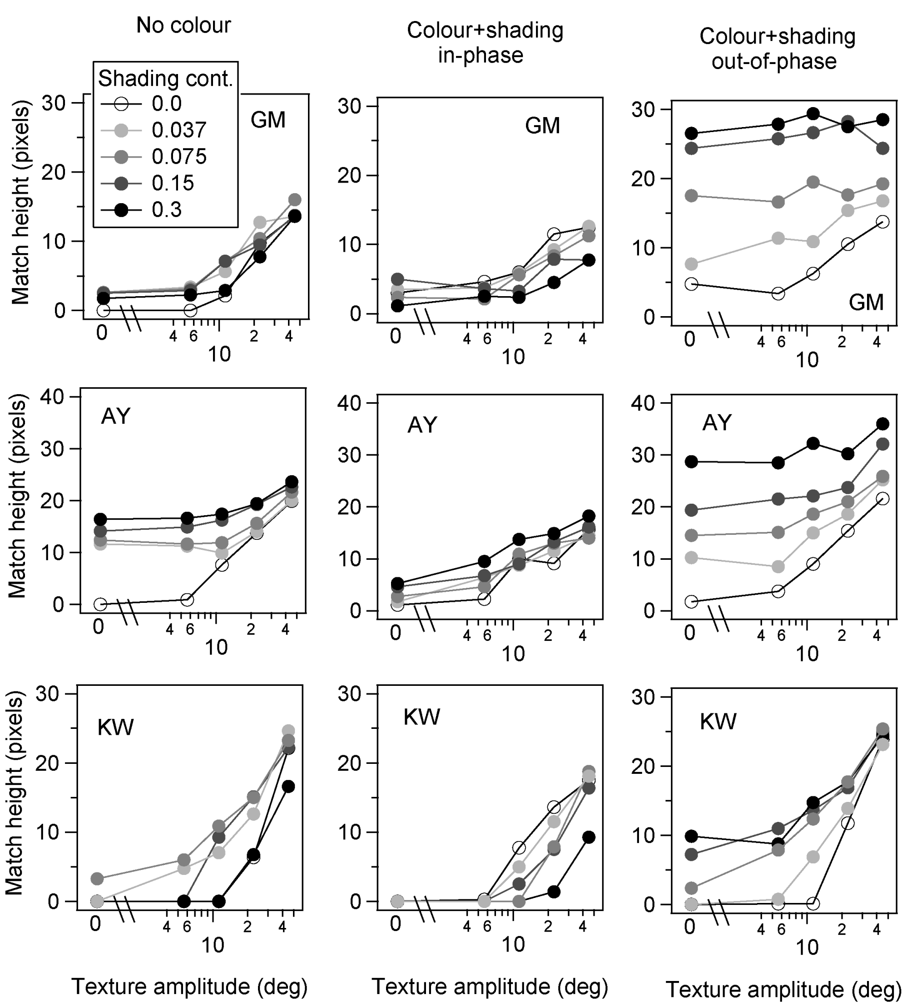

Figure 3. Results obtained using the adjustable bar method. The ordinates in each plot give perceived depth in terms of bar height. Otherwise, the plots and symbols are the same as in Fig. 2.

other subjects, but in spite of this the overall influence of colour contrast on her results is consistent with the other subjects.

Consider now the effects of colour contrast. When compared to the no-colour condition, adding colour contrast in-phase with the shading reduced perceived depth, whereas adding colour contrast out-of-phase with the shading increased perceived depth. These effects appear to be robust across subjects and method. A particularly noteworthy aspect of the data is that adding colour contrast out-of-phase with the shading causes the different shading contrast conditions to spread out vertically. In other words out-of-phase colour contrast results in shading contrast having a more differentiated impact on perceived depth.

One of the aims of this study was to determine the extent to which the colour-shading effect operated when cues to surface shape other than shading, specifically orientation-based texture variation, were present. In order to put the data into a manageable form that gives an indication of the impact of colour contrast on perceived depth in the context of texture amplitude, we performed the following analysis. For each shading contrast we subtracted the raw no-colour settings from both the colour in-phase and colour out-of-phase settings. We also performed the same subtractions with logarithmically transformed values, in order to determine whether there was a proportionate, rather than absolute change in the impact of colour with texture amplitude. We then averaged the subtracted results across (a) all positive shading contrasts and (b) subjects. The same analysis was performed separately for the no shading (zero shading contrast) conditions, though only using raw values, as there were insufficient data points with positive values to justify the logarithmic analysis. The results are shown in Fig. 4. The two graphs on the left show the differences in raw values for the conditions in which shading was absent, the two graphs in the middle the differences in log values for the non-zero shading contrasts, and the two graphs on the right the differences in raw values for the no shading contrasts. The top graphs are for the stereo matching procedure, the bottom graphs for the adjustable bar procedure. Squares are for the differences between the no colour and in-phase conditions, circles for the differences between the no-colour and out-of-phase conditions.

Four features of Fig. 4 are worth noting. First, when shading is present, colour contrast has a pronounced and consistent phase-dependent effect on perceived depth. This is evidenced by the separation between the in-phase and out-of-phase plots in the four left-hand graphs, with no overlap in standard errors. Second, colour contrast has no significant *phase-dependent* impact on perceived depth when shading is absent, as indicated by the closeness of the in-phase and out-of-phase plots in the two right hand graphs. Although in the lower right hand graph there is an apparently significant colour phase effect at the highest texture amplitude, this is a lone data point and arguably best ascribed to chance. Third, the impact of colour contrast when shading is present is more-or-less constant across texture amplitude for the raw (linear) values, but decreases slightly for the log transformed data, i.e. decreases slightly when computed proportionately. Fourth, both measurement

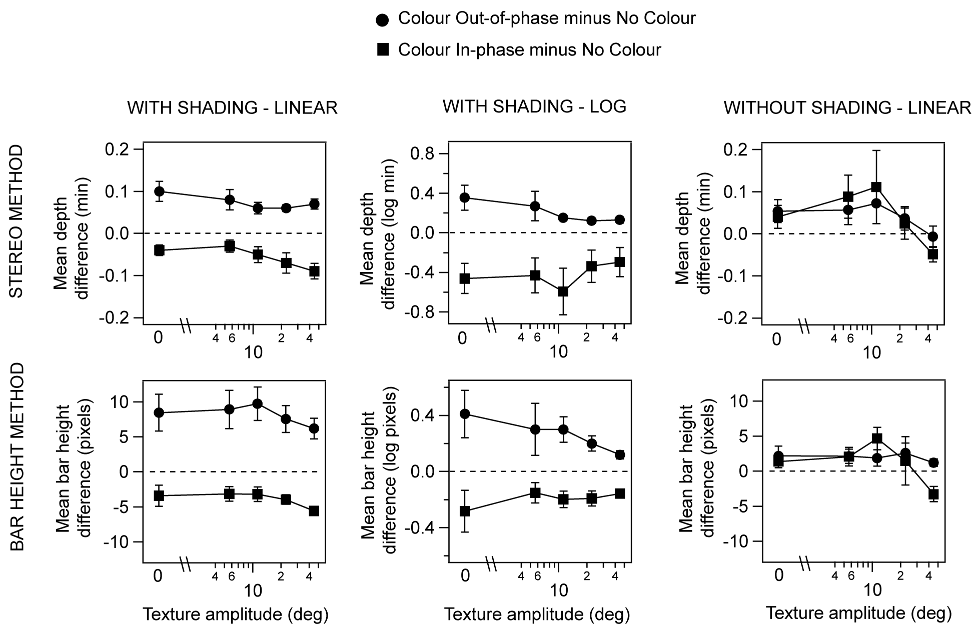

Figure 4. Left and middle panels show the mean differences, calculated across shading contrast and subject, between the no-colour and with-colour contrast conditions. The right-hand panels show the mean differences between the no-colour and with-colour contrast conditions for just zero shading contrast. The top graphs are for the stereo-grating matching procedure, the bottom graphs for the adjustable bar procedure. Filled squares are the mean differences between the no-colour and in-phase conditions, filled circles the mean differences between the no-colour and out-of-phase conditions.

techniques produce more-or-less similar results, as evidenced by the similarity between the top and bottom sets of graphs.

DISCUSSION

The results of the present study can be summarised as follows.

(1) Colour contrast has a phase-dependent influence on perceived depth in patterns that combine shape-from-shading with shape-from-texture.

(2) The influence of colour contrast on perceived depth is similar across texture amplitude when computed linearly, but diminishes slightly with texture amplitude when computed proportionately.

(3) Colour contrast has no phase-dependent influence on perceived depth in the absence of shading.

That colour contrast has a phase-dependent influence on perceived shape confirms previous findings using patterns that contain only colour and luminance contrast (Kingdom, 2003; Kingdom *et al.*, 2005), and extends the findings to the situation where texture is an additional cue to surface shape. In the experiments here, we only

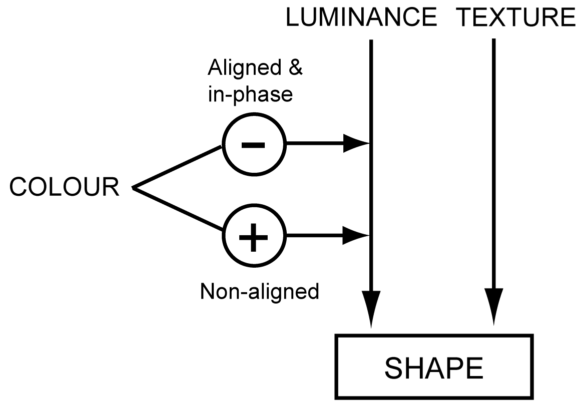

Figure 5. Schematic model of the conclusion of the study.

employed in-phase (0 or 180 deg) or out-of-phase (90 or 270 deg) relations between the colour and luminance gratings. Based on the results of Kingdom (2003), we would expect that other phase relationships would produce results intermediate between maximum depth-suppression and maximum depth-enhancement, with no depth-suppression or depth-enhancement (i.e. no effect of colour contrast) for phase differences of 45, 135, 225 and 315 deg. That colour contrast has no phase-dependent influence on pure shape-from-texture, i.e. when no shading is present, is a new, though not unexpected finding. On ecological grounds it is hard to see why chromatic variations should influence perceived shape-from-texture, because textural variation is invariably a surface rather than illumination property.

We found that *in the presence of shading* the magnitudes of both colour-driven depth-enhancement and colour-driven depth-suppression were more-or-less constant across texture amplitude when computed linearly, and diminished slightly with texture amplitude when computed proportionately. These findings are broadly compatible with the idea that perceived depth involves the weighted sum of shading and texture cues, with the shading cue weighted according to the robustness of the shading interpretation (see Landy *et al.*, 1995). In this scheme colour contrast promotes, or inhibits the shading interpretation based on its spatial relationship with the luminance pattern. The essential relationship between colour, shading and texture revealed by the present study is illustrated in Fig. 5. The figure demonstrates that chromatic variations impact on the contribution of luminance variations to perceived shape in combined shape-from-shading and shape-from-texture patterns, but do not impact on shape-from-texture itself.

Although the principal aim of our study was to investigate the impact of colour contrast on perceived depth in shading/texture patterns, our results support the well-attested observation that orientation variations elicit strong impressions of surface curvature (Stevens, 1988; Li and Zaidi, 2000; Mamassian and Landy, 2001). To what do these impressions of surface curvature correspond, in terms of geometry? The visual system is presumably making the assumption that the

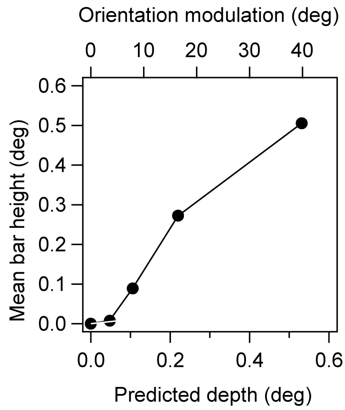

Figure 6. Actual versus predicted settings of bar height for the texture-only conditions, according to a model that assumes that the orientation variations in the stimuli arise from the projection of straight lines lying on a sinusoidally folded surface, slanted 53 deg away from the observer. See text for details.

orientation variations in the stimuli arise from the projection of straight contours that lie across an undulating surface, whose folds are oriented obliquely and are slanted away from the observer. It can be shown that if the surface is folded sinusoidally, the local orientations, i.e. tangents of the contours, are near-sinusoidal, with an amplitude of orientation modulation a_θ given by $\tan^{-1}[a_s 2\pi f \sin(s_\theta)]$, where a_s is the amplitude of surface modulation, f its spatial frequency, and s_θ the slant of the surface away from the fronto-parallel (upright) plane. The effect of s_θ assumes parallel projection. By inverting this equation we obtain the amplitude of surface modulation that would give rise to a given amplitude of orientation modulation, i.e. $a_s = \tan(a_\theta)/2\pi f \sin(s_\theta)$. If we now assume that our subjects' settings reflected the perceived depth, i.e. distance between the peaks and troughs of the surface modulation, then we can determine how well these settings are predicted by (twice) the values of a_s calculated from the above equation for any surface slant s_θ. Figure 6 shows the average subject's settings obtained from the no-colour, zero-shading-contrast conditions using the bar-height adjustment method. These are plotted, in degrees, against $2a_s$, also in degrees, for a slant of 53 deg — the value which produced the closest absolute match between the predicted and actual settings. The settings are reasonably well predicted. However, although the near-linear relationship between predicted and actual settings revealed in Fig. 6 is consistent with the model described above, the 53 deg estimate of perceived slant should be treated with caution, as there are many stimulus factors that are likely to affect the 'gain' of perceived depth, such as the use of randomly positioned micropatterns rather than parallel contours, and these will affect the estimate of perceived slant.

The unique and positive role that colour vision appears to play in the perception of shape-from-shading in our mixed shading and texture patterns is pertinent given that colour vision is traditionally considered the poor cousin of luminance vision in its capacity to provide information about the third dimension, i.e. depth. For example, stereoscopic depth judgements of isoluminant stimuli are generally worse than those with isochromatic stimuli (Lu and Fender, 1972; Gregory, 1977; Livingstone and Hubel, 1987; Kingdom and Simmons, 2000). The results here demonstrate that colour vision *in combination* with luminance and texture can significantly enhance impressions of depth. This positive role of colour vision in the perception of depth complements other positive roles in the analysis of image-structure, such as in the detection of fruit and flowers in foliage (Mollon, 1989; Sumner and Mollon, 2000; Domini and Lucas, 2001), the identification of shadows (Kingdom, Beauce and Hunter, 2004) and the memory of scenes (Gegenfurtner and Rieger, 2000).

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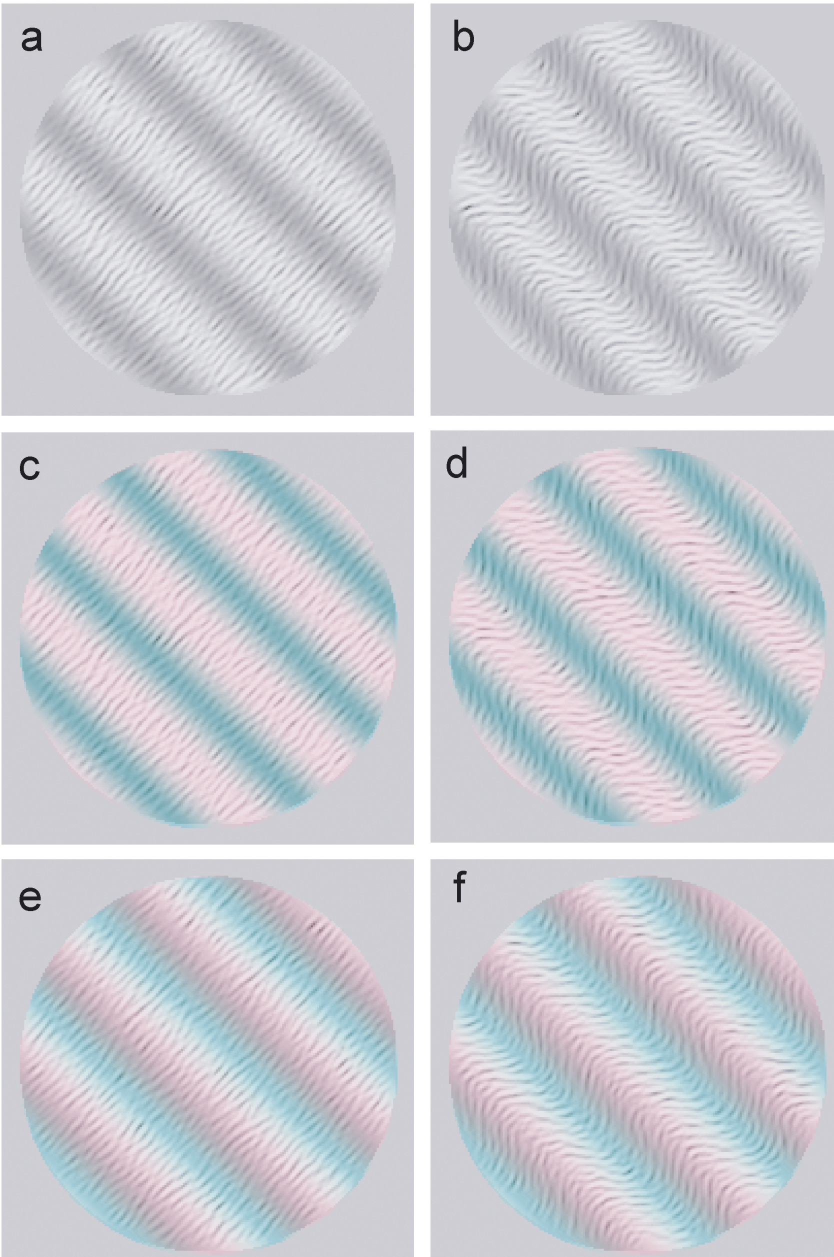

Kingdom *et al.*, Figure 1.