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On the interference of task-irrelevant hue variation on texture segmentation

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Abstract. Although natural images often include discordant information about object boundaries, the majority of research on texture segmentation has involved variation along a single dimension, eg colour, orientation, size. In this study, we examined orientation-based texture segmentation in the presence and absence of task-irrelevant colour variation. Previously, it had been shown that orientation-based texture segmentation was impaired if the elements, normally of one colour, were randomly allocated one of two colours (Morgan et al, 1992 *Proceedings of the Royal Society of London, Series B* **248** 291 – 295). We found that this interference disappeared, however, when the spatial pattern of the colour variation was regular, as opposed to random, and when the elements were randomly positioned. We consider four models of how relevant and irrelevant texture information might combine to produce the interference effect, with special regard to these new findings. None of the models could account for the dependency of the interference effect on the spatial arrangement of colour and orientation in the texture. We suggest that inter-element separation and spatial-frequency selectivity are critical variables in the interference effect.

1 Introduction

One of the primary goals of vision is to segment the world, as represented in the retinal image, into objects and surfaces. As a consequence, a great deal of effort has been expended in attempting to describe those stimulus properties that allow us to segment one object or surface from another. One of those properties is spatial structure or texture. Texture has been described as the repetition of similar elements across a surface, and texture differences as those that can be identified in the absence of a difference in colour, luminance, motion, or disparity. One example of a texture difference is two regions that differ in the orientations of their elements. Given a large difference in orientation, the elements appear to segment into two distinct regions (see figure 1a). The approach of studying texture perception in isolation, that is using stimuli defined only by texture differences, has been very fruitful. However, in the natural world the retinal image is rarely homogeneous in all but one dimension; moreover, information from different dimensions is frequently discordant, and yet we still segment the natural world into separate objects and surfaces. Studying the effects of variations in multiple dimensions may further our understanding of the mechanisms which underlie the segmentation of surfaces. Towards this end, in the present study we examined the interference effect, in which irrelevant variations along one dimension are found to interfere with texture segmentation based upon another (Callaghan et al 1986; Morgan et al 1992; Pashler 1988; Theeuwes 1992). One example is illustrated in figure 1b. Typically, observers find that the irrelevant chromatic variation in the figure interferes with texture segmentation (Morgan et al 1992).

Since the luminance of a surface often varies as a consequence of changes in illumination, whereas the colour of the surface rarely does (Mollon 1989; Morgan 1991; Mullen and Kingdom 1991; Switkes and De Valois 1983), it is likely that colour plays a key role in the segmentation of natural scenes. The few studies that have explored

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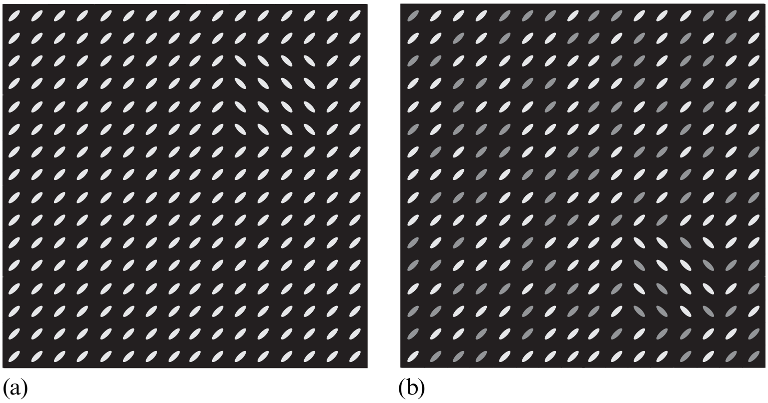

Figure 1. Illustration of the interference effect. Both stimuli contain a patch in which the elements are different in orientation from the rest of the display. However, the patch is harder to detect when the colour of the elements is randomly varied (b) than when the colour of the elements is uniform (a).

the role of colour in texture segmentation have reported that colour can mediate texture segmentation in the absence of luminance information (Lushcow and Nothdurft 1988, 1993; McIlhagga et al 1990), and that colour is processed independently from luminance in texture tasks (Li and Lennie 1997) and visual-search tasks (Duncan and Humphreys 1989, 1992; Nagy and Sanchez 1990; Nagy et al 1990; Treisman and Gelade 1980; Treisman and Sato 1990).

The interference effect in figure 1 is clearly not consistent with the idea that different dimensions are processed and accessed independently since, if they were, the figure should segment equally well in the presence or absence of irrelevant chromatic variation. Of the researchers dealing with interference effects, only Pashler (1988) has investigated its possible mechanism. However, Pashler (1988) used a visual-search task rather than a texture-segmentation task. Since the properties of visual search have been shown to differ from those of texture segmentation in a number of ways (Duncan and Humphreys 1992; Wolfe 1992, 1994), the mechanism underlying the interference effect in texture segmentation remains unclear. Nonetheless, a number of researchers have argued that interference effects support particular models of visual search or texture segmentation (Callaghan et al 1986; Morgan et al 1992; Pashler 1988; Theeuwes 1992; Wolfe 1994), and it is worth considering these in some detail.

Figure 2 illustrates four models, all characterised by a two-stage process. The dimensions of the stimulus (eg colour, orientation, luminance) are encoded in the first stage, while the second stage generates a representation of the location of local contrasts within a dimension or dimensions, which are then used to localise the target. None of the models would predict an interference effect if each dimension was represented independently and one had direct access to all the dimensions at the first stage. Therefore, a property of all the models is that one only has access to the results of the second stage. This precludes conclusions about whether dimensions are encoded independently or conjoined at the first stage (see Duncan and Humphreys 1992, for a similar view).

The model shown in figure 2a suggests that the interference effect may be due to our tendency to attend to only one dimension at a time (eg colour rather than orientation, or vice versa) (Morgan et al 1992). The selected dimension may simply be the one which 'grabs one's attention', for example because it has the higher contrast. We refer to this as the 'attention-to-single-dimension' model. Therefore, although more than one dimension may be initially encoded in parallel, we are unable to simultaneously attend to both representations when extracting a global property of the stimulus.

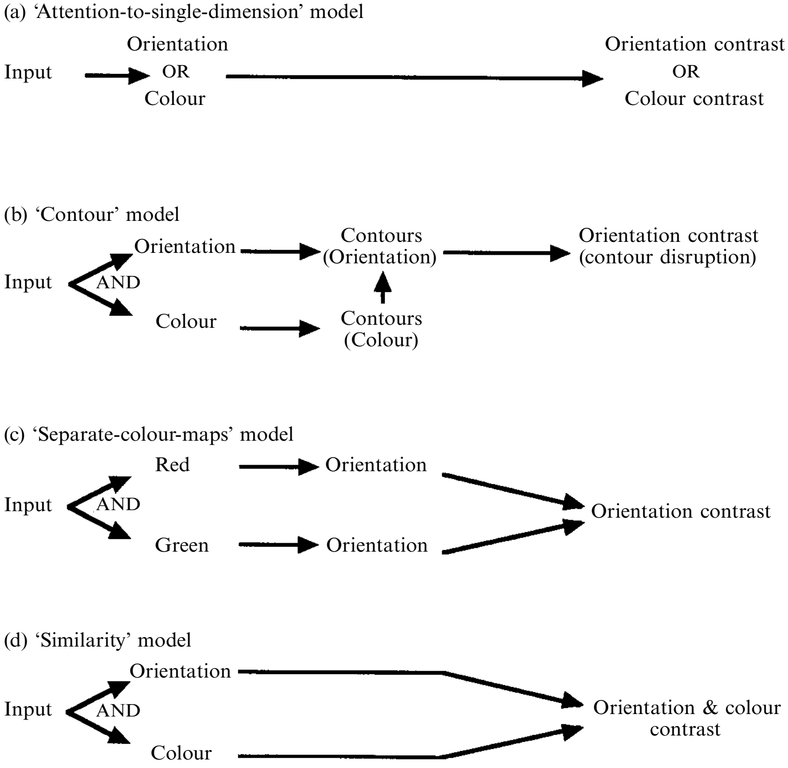

Figure 2. Models that may account for interference between orientation and colour are represented. Each model posits a two-stage process: the encoding of dimensions in the first stage is followed by the construction of a representation similar to the activation map of Wolfe (1994) in which possible locations of the target are represented. See text for more detail.

In support of this model, Morgan et al (1992) noted that our first impression of a stimulus similar to that shown in figure 1b is of a display that is grouped into differently coloured regions. Callaghan et al (1986) and Theeuwes (1992) reported that interference only occurs when the variation in the irrelevant dimension is at least as discriminable as the difference in the dimension that defines the target. Since varying discriminability should influence which dimension is attended to first, these results also support the model.

The model shown in figure 2b suggests that the interference effect is a consequence of our inability to form contours from elements with different colours. We term this the 'contour' model. A number of approaches to segmentation rely on a process in which local edges are detected and integrated to form boundaries (Grossberg and Mingolla 1985; Heitger and von der Heydt 1993; Marr 1982). In the model here, segmentation is assumed to be based upon the disruption of contours formed from co-aligned elements (Beck et al 1989; Field et al 1993). When the elements that form a contour are randomised in colour, it has been shown that the processing of contours is degraded (McIlhagga and Mullen 1996; Mullen et al 2000).

The model in figure 2c is referred to as the 'separate-colour-maps' model and posits that texture segmentation is carried out separately for the red and green elements of the stimulus. This would result in each colour representation having a reduced density and an increase in the variance of between-element distances, both of which could decrease texture-segmentation performance (Nothdurft 1985). Ecologically, early segmentation based upon hue differences appears to make sense since the colour of objects is often relatively homogeneous across an object's surface (Mollon 1989; Morgan 1991; Mullen and Kingdom 1991). Supportive evidence for an early segmentation based upon colour includes demonstrations that colour can be used to improve performance when colour defines a portion of the set of distractors (Duncan and Humphreys 1992; Wolfe et al 1989).

In contrast to the previous three models, the model in figure 2d suggests that all dimensions are encoded independently and can be accessed in parallel. In acknowledgment of a number of models based on analogous ideas (Beck 1982; Callaghan et al 1986; Duncan and Humphreys 1989, 1992; Enns 1986; Wolfe 1994), we refer to this model as the 'similarity' model. Consistent with a number of models of texture segmentation (Caelli 1985; Sagi and Julesz 1987; Ullman 1984; Wolfe 1992), similarity models hold that a difference along any dimension between any two neighbouring elements indicates a potential location of the target. Consequently, texture segmentation or visual search is enhanced: (i) when the similarity between the background elements and the elements which define the target is low and (ii) when the similarity of elements within a region, either the target or background, is high. Thus, when the colour of the elements is randomly varied, the differences in colour provide additional, but incorrect, potential locations for the texture boundary, resulting in a decreased signal-to-noise ratio and deficits in texture segmentation. Although the specifics of similarity models differ considerably, each embodies the above two principles and would predict interference effects similar to those observed by Callaghan (1984, 1989; Callaghan et al 1986) and Morgan et al (1992).

The aim of the present investigation is to provide new behavioural data on the colour interference effect in texture segmentation to evaluate the four models described above.

2 Methods

2.1 *Participants*

The two authors, PMP and FAAK, and one other highly experienced psychophysical observer, RK, participated in all conditions. Two naïve observers, CC and AA, participated in a small subset of the conditions. All observers had normal or corrected-to-normal acuity and normal colour vision.

2.2 *Stimuli*

The stimuli were generated with a VSG2/3 video-graphics board (Cambridge Research Systems) and presented on a flat-screen colour monitor (Sony F500 Trinitron). Only the red and green phosphors were used, and these were gamma-corrected with an optical photometer (model OP200-E, Cambridge Research Systems). The CIE coordinates of the red and green phosphors were $x = 0.610$, $y = 0.340$ and $x = 0.280$, $y = 0.595$, respectively. Maximum screen luminance was 12.68 cd m^{-2}.

The stimuli used in the ten conditions are illustrated schematically in figure 3. Each texture comprised 30×30 oriented Gaussians. The Gaussians had a $2:3$ aspect ratio and subtended 0.06 deg $\times$ 0.09 deg at a viewing distance of 91 cm. These were presented on a black background. In each condition, the elements constituting the target were mirror-reversed versions of those which constituted the remainder of the display. To avoid the possibility that texture segmentation could have been accomplished from small luminance differences for differently oriented ellipses due to small horizontal–vertical differences in the raster, all elements were mirror-reversed relative to a vertical axis. The orientation difference between the background and target elements was set individually for each of the subjects so as to obtain approximately 80% correct with stimulus 3a ($45° - 60°$ orientation difference).

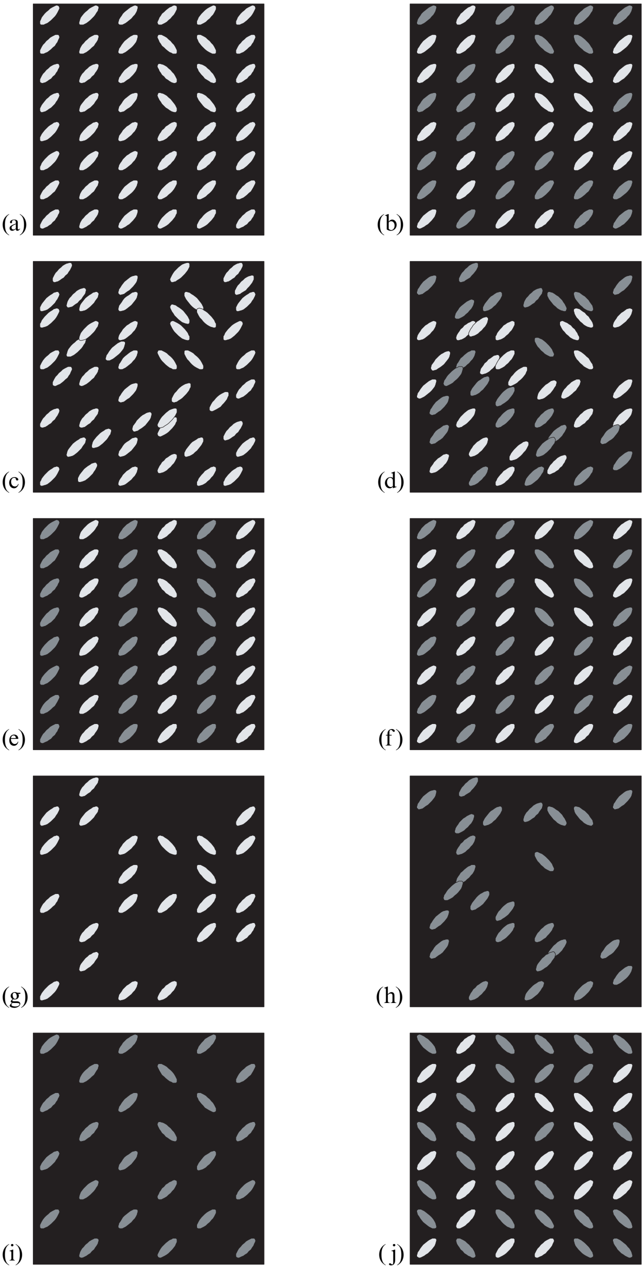

Figure 3. Representations of the ten stimulus conditions used in this experiment: (a) one colour and regularly spaced; (b) random colour variation and regularly spaced; (c) one colour and randomly positioned; (d) random colour variation and randomly positioned; (e) spatially regular variation in colour (stripes); (f) spatially regular variation in colour (checkerboard); (g) as in figure 3b but with elements of one of the colours removed; (h) as in figure 3d but with elements of one of the colours removed; (i) as in figure 3f but with elements of one of the colours removed; and (j) conjunction condition in which the background is composed of red right-obliques and green left-obliques while the target is composed of red left-obliques and green right-obliques.

The first pattern, shown in figure 3a, consists of elements of one colour and was used to measure baseline texture-segmentation performance in the absence of irrelevant colour information. Figure 3b shows the stimulus used to quantify the interference effect; the colour of the elements was randomly varied. Subsequent conditions tested the four models of the interference effect. Conditions 3c and 3d are identical to those in 3a and 3b, except the elements are randomly positioned rather than regularly spaced. The random placement of elements in conditions 3c and 3d was included as a test of the contour model since the randomly positioned elements are not easily aligned, degrading the ability to use contours to segment the texture. In addition, conditions 3d and 3b contain similar amounts of noise and, hence, condition 3d also tests the similarity model. In conditions 3e and 3f, the elements that constitute the texture are regularly spaced but the colour variation is spatially regular (ie stripes or checkerboard) rather than spatially random. Since the spatially regular colour variation results in colour contrasts equal to condition 3b and a similar pattern of colour variation was shown to disrupt the integration of contours, these conditions (3e and 3f) were selected for the assessment of the attention-to-single-dimension and contour models, respectively. Conditions 3g, 3h, and 3i were included to assess the separate-colour-maps model which assumes segmentation operates separately on each colour. The final condition (figure 3j) is a conjunction condition, as the target is defined by the conjunction of colour and orientation (eg left-oblique red, right-oblique green for the target; left-oblique green, right-oblique red for the background, or vice versa). Unlike the other conditions with elements of both colours, the colour variation in the conjunction condition is not irrelevant. This conjunction condition further tested the separate-colour-maps model since, if orientation contrast was calculated separately for elements of each colour, performance in this condition should equal that in condition 3b.

2.3 *Procedure*

Percentage-correct scores for each of the ten conditions were measured by a four-alternative forced-choice procedure in which the participants were asked to indicate the quadrant of the display that contained an orientation-defined texture patch. The probability that the target was located in a given quadrant on any trial was 0.25 and the target was presented in each of the quadrants an equal number of times. The stimuli were presented for 150 ms. Trials were run in blocks of 100 trials, in which only one of the ten types of stimulus pattern was presented. The order in which the blocks were presented was random. Each participant completed 300 trials for each of the ten stimulus types.

2.4 *Data analysis*

Percentage-correct scores were calculated across the three blocks of 100 trials run for each of the ten conditions.

In order to test the separate-colour-maps model illustrated in figure 2c, it was necessary to make predictions based on probability summation. If the visual array is filtered into separate red and green maps in which colour and orientation are conjoined, as illustrated in figure 2c, then the probabilities of target detection with red and green elements both present ($P_{\mathrm{r\ and\ g}}$) should be predictable from the probabilities (P) of target detection with red (r) and green (g) presented alone. Probability summation was calculated as:

$$P_{\mathrm{r\ and\ g}} = 1 - \frac{1}{1 - 0.25}(1 - P_{\mathrm{r\ or\ g}})^2 ,$$

where $P_{\mathrm{r\ or\ g}}$ refers to the mean probability of red-alone and green-alone target detection.

3 Results

Percentage-correct scores for each of the ten conditions are shown in figure 4. Performance was worse for condition 3b than for 3a, which confirms the interference effect for regularly spaced elements. However, the results of conditions 3c and 3d show an absence of the interference effect when the positions of the elements were random. Moreover, the interference effect disappears when the different colours form stripes or a checkerboard (conditions 3e and 3f). Figures 4g through 4i show the results obtained when only one colour was present. Although inspection of the stimuli in 3g to 3i suggests that removal of one of the colours is more detrimental when the colour variation is random (3g and 3h) than when the colour variation forms stripes or a checkerboard (3i), the results clearly show that performance is similar in all three conditions. The data in figures 4g through 4i were used to calculate probability-summation predictions

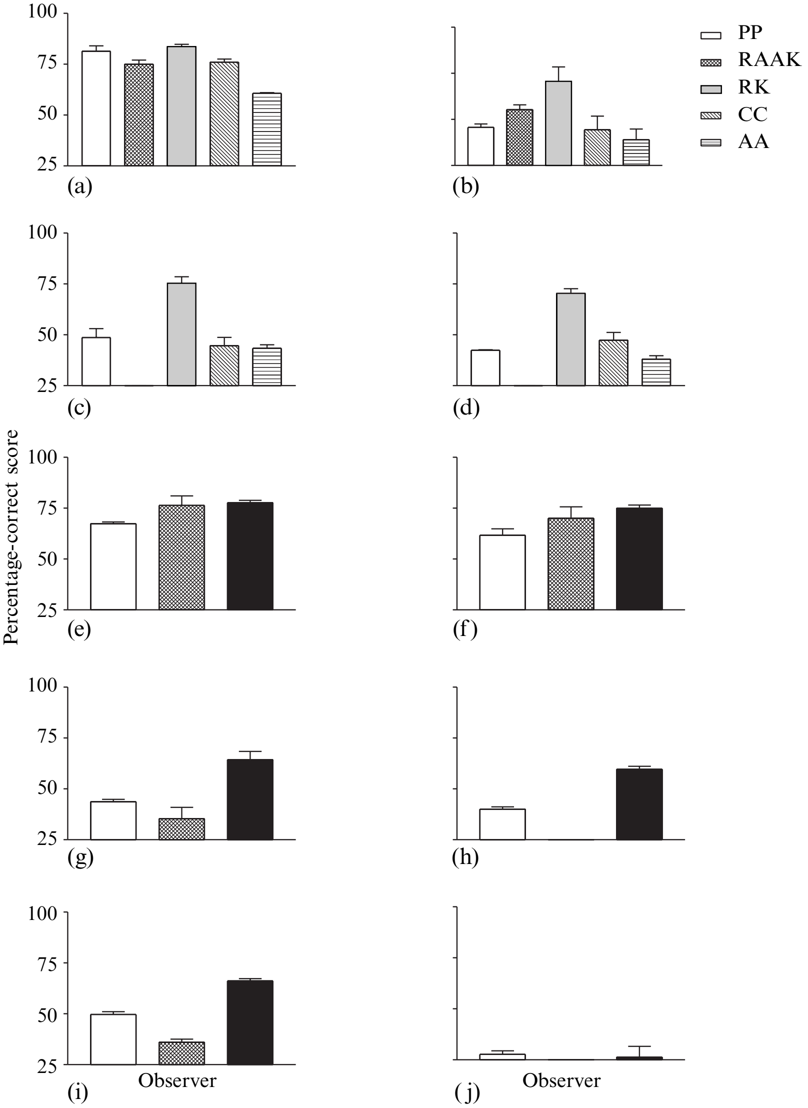

Figure 4. The percentage of trials on which each of the observers correctly reported the quadrant which contained the target. The graphs lettered (a) through (j) represent the data from the stimulus conditions shown in figure 3 labeled with the same letters. Error bars represent ±1 standard error of the mean.

and are compared, in figure 5, to performance when both the red and green elements were presented simultaneously (conditions 3b, 3d, and 3f, respectively). Performance in the conjunction condition (3j) is also compared to the probability-summation prediction for a spatially random variation in colour (4g) in figure 5. Performance with both red and green elements is not well predicted by the probability-summation estimates. In summary, the interference effect disappears when (a) the elements are randomly positioned and (b) when the colour variation is spatially regular. Furthermore, the interference effect is not well predicted on the assumption that individual colour/orientation maps are processed separately.

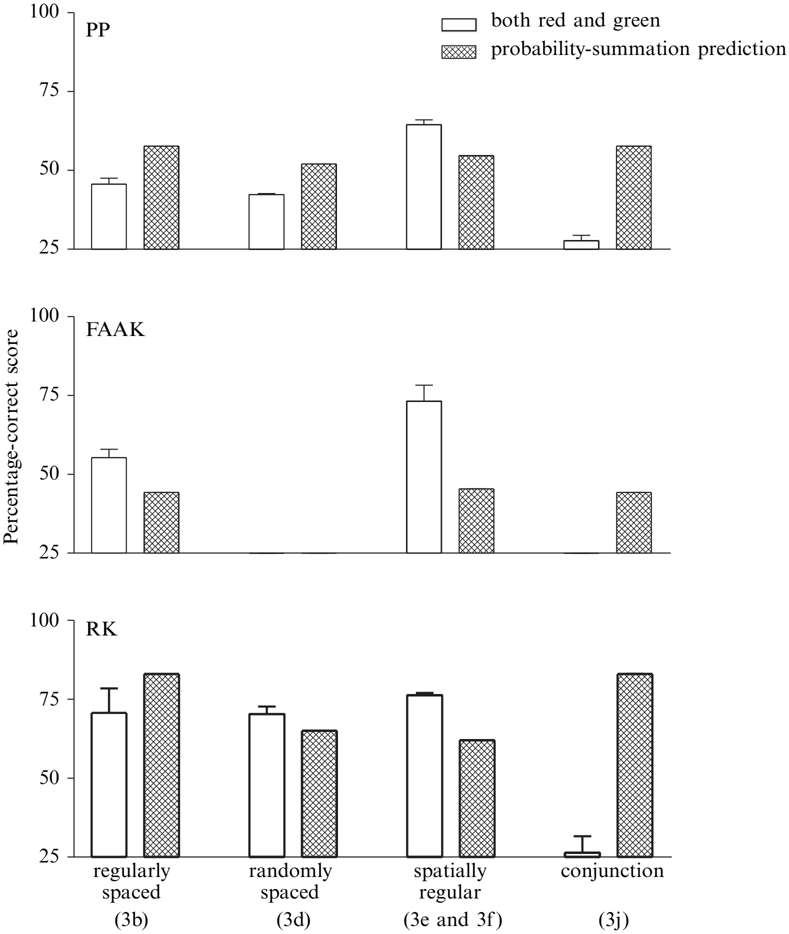

Figure 5. Probability-summation predictions (based upon percentage-correct scores when elements of only one of the colours are presented) and performance with both red and green elements are shown in separate panels for each of the observers. Error bars represent ±1 standard error of the mean.

4 Discussion

The 'attention-to-single-dimension' model in figure 2a suggests that the interference effect is a consequence of our inability to attend to more than one dimension at a time (Morgan et al 1992). This model, however, predicts that the form of the irrelevant colour variation should not affect the magnitude of the interference effect. Clearly, the data do not support this prediction since spatially regular variations in colour (conditions 3e and 3f) produced a less marked interference effect than spatially random variations (condition 3b). Therefore, it appears that the interference effect cannot be accounted for by the attention-to-single-dimension model.

The 'contour' model presented in figure 2b suggests that the interference effect is a consequence of the colour variation disrupting the ability to form contours. Consistent with the contour model, the interference effect was absent when the elements were positioned randomly and contours would be expected to play less of a role. However, there was no interference effect with the spatially regular variations in colour (ie stripes and checkerboard), even though such patterns of colour variation are similar to those found to significantly disrupt contour detection (Mullen et al 2000). Therefore, we reject the contour model as a plausible explanation for the interference effect.

The 'separate-colour-maps' model in figure 2c suggests that the interference effect results from the early segmentation of the visual array into separate representations for red and green. To test this model, we compared performance with red and green elements presented together with probability-summation predictions from performance with only red or green elements present. Figure 5 shows that the probability-summation predictions were not met. Although the mean performance across observers is consistent with the probability-summation predictions in the regularly spaced and randomly positioned conditions, the results for spatially regular colour variations demonstrate overadditivity when both colours are combined. However, the most compelling evidence against the separate-colour-maps model is the conjunction condition (figure 5), where each colour provides an adequate representation of the texture (equivalent to that in condition 3b), yet where performance is at chance level. In summary, the results cannot be accounted for by the separate-colour-maps model.

The 'similarity' model in figure 2d suggests that potential texture boundaries are located where neighbouring elements differ significantly along any dimension (Beck 1982; Callaghan et al 1986; Duncan and Humphreys 1989, 1992; Enns 1986; Wolfe 1994). Therefore, any irrelevant colour variation will introduce spurious locations of the texture border, decreasing the signal-to-noise ratio. However, we found that random variation in colour impaired texture segmentation only when the elements were regularly spaced, even though similar increases in noise associated with the texture-border location would be expected for both random and regular element positioning. Moreover, if the irrelevant colour variation increased the number of false texture targets then it would be expected to do so equally for spatially regular and spatially random colour variations (figures 3e versus 3f). Again, the data do not support this prediction. So, it appears that the similarity model cannot account for our results.

In summary, the results cannot be parsimoniously explained by any of the four models in figure 2, with the results from the randomly positioned stimuli (3c and 3d) and the spatially regular colour variation (3e and 3f) being the main obstacles.

What then is the explanation of the interference effect? Specifically, how can we explain why either randomly positioning the elements, or using spatially regular irrelevant colour variation, eliminates the effect, when the attention-to-single-dimension, contour, separate-colour-maps, and similarity model explanations do not suffice? Although we are unable to provide an explanation, it is worth considering what might be the critical stimulus characteristics underlying our results. Nothdurft (1985) had suggested that texture gradients and texture-segmentation performance are dependent upon the distance between elements. The irregular spatial structure in our randomly positioned textures introduces variability in the inter-element distances, and this might result in an overall decrease in the contrast or gradient defining the border of the texture patch. Indeed, performance with the randomly positioned textures was below that for the regularly positioned textures. But exactly why a weakening of the texture border through random positioning should eliminate the interference effect remains unclear.

The interference effect was also eliminated when the colour variation was spatially regular; in other words the form of the colour variation appears to be crucial. Pashler (1988) and Nothdurft (1997) have suggested that texture channels may be spatial-frequency selective [as has been shown to be the case for luminance mechanisms (eg Blakemore and Campbell 1969)], and thus texture segmentation may only show interference effects if the relevant and irrelevant dimensions are similar in spatial frequency. Wolfe's (1994) model of visual search incorporates filters of a fixed size which would be expected to combine information from different dimensions only when similar in spatial scale. Hence, random variation in an irrelevant dimension may mimic the target patch in terms of spatial scale better than with spatially regular variations.

In conclusion, we have demonstrated that spatial variations in colour interfere with orientation-based texture segmentation when the elements are positioned regularly, but not randomly, and when the colour variation is random, but not regular. These results argue against explanations of the interference effect based on (a) competing attention between different dimensions, (b) the disruption of contour integration, (c) separate processing of differently coloured elements, and (d) the introduction of spurious texture-border signals. Further research will explore the possibility that inter-element separation and spatial-frequency selectivity are critical variables for producing the interference effect.

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