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Does segregation by colour/luminance facilitate the detection of structure-from-motion in noise?

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Abstract. The aim in the experiments was to examine whether the detection of structure-from-motion (SFM) in noise was facilitated when target and noise were segregated by colour and/or luminance polarity. The SFM target was a rotating 'V-shape' structure simulated with limited-lifetime Gaussian micropatterns and embedded in random-motion noise. Threshold levels of V-shape slant were measured for stimuli in which target and noise were segregated or unsegregated by colour/luminance, and under two conditions, with and without static form cues to the SFM target. The presence or absence of static form cues to the SFM target was manipulated by varying the relative numbers of micropatterns in target and noise. In the absence of static form cues, segregation of target and noise by colour and/or luminance polarity did not facilitate target detection, even when subjects knew which micropatterns belonged to the target. On the other hand, when static form cues were present, segregation improved performance. These results imply that SFM processing is 'form-cue invariant' except when the target form is immediately identifiable in the static view of the stimulus. The significance of the results for understanding the role of colour vision in breaking camouflage and in 'grouping' is discussed.

1 Introduction

The projected two-dimensional (2-D) motion of a moving object provides the visual system with information about the three-dimensional (3-D) structure of the object, a process referred to as structure-from-motion, or SFM (Wallach and O'Connell 1953; Braunstein 1962; Rogers and Graham 1979; Todd 1984; Ullman 1984). The recovery of SFM often involves integrating the relative motions of many parts of the object, such as would happen if it were partially camouflaged. In natural visual scenes, however, an object will often differ from its background in other ways besides motion, eg colour, luminance, orientation, scale, binocular disparity. How do these additional dimensions facilitate our ability to extract SFM? In this study we examine whether segregation of an object in noise by colour and/or luminance polarity facilitates the detection of its SFM.

The role of colour vision in SFM has not been studied as extensively as in more basic motion tasks, such as the detection of motion direction. Moreover, the role of colour vision in motion processing has been examined primarily at isoluminance, that is, when the stimuli are only defined by colour contrast. Generally, motion perception is weak at isoluminance compared with when luminance based, but there is nevertheless clear evidence for a chromatic input to motion processing (Cavanagh and Favreau 1985; Saito et al 1989; Palmer et al 1993; Morgan and Ingle 1994; Cropper and Derrington 1996). That colour might be useful for SFM has support from studies by Wuerger and Landy (1993) and Cavanagh et al (1995). Wuerger and Landy measured the ability to infer SFM in several directions in 3-D colour space by using a shape-identification task. They showed that the input to SFM from cones sensitive to short wavelengths is negligible and that SFM mechanisms use the output of two mechanisms, one taking the difference between signals from cones sensitive to the long and medium wavelengths and the other taking the respective sum. Cavanagh et al also found that depth from motion parallax could be perceived at isoluminance. However, our interest here is not whether pure colour information activates SFM mechanisms, but whether the detection of SFM benefits from having 'target' and 'noise' differently coloured when the component micropatterns are luminance defined. From now on we will use the terms 'segregated' to refer to the situation where target and noise have different colours or luminance polarities, and 'unsegregated' when they do not. The segregation of target and noise by colour/luminance polarity indicates physical segregation, and not necessarily perceptual segregation.

Croner and Albright (1997) recently showed that discrimination of 2-D coherent motion was facilitated when target and noise dots differed in colour compared with when they were the same. However, in their paradigm the number of signal dots required to reach the threshold for detecting motion direction was typically very low ($<5\%$), and thus in the colour-segregated condition the signal dots would be visible in a stationary frame of the stimulus even if their colour were unknown, as they were in such a minority. In other words there was a 'pop-out' static form cue to the signal. But what if the signal and noise were segregated by colour, but there was no such static form cue to the signal? Such a situation would occur for example if there were equal numbers of signal and noise dots, and the subject did not know which type of dot belonged to the signal and which to the noise. Would motion perception be facilitated by segregation along the colour/luminance dimension under these circumstances? If it was, then this would suggest that motion mechanisms automatically grouped similarly coloured features for SFM perception. In examining whether segregation of target and noise facilitates the detection of SFM, we therefore argue that one must distinguish two situations, the first in which colour/luminance differences provide a static form cue to the target, the second when they do not.

In the experiments of this study subjects were required to detect a rotating 3-D 'V-shape' random-dot structure in noise. Target and noise dots were luminance defined, but could differ in colour and/or luminance polarity. The display background to which observers adapted was always yellow (the mean of red and green). We examined both the situation in which colour/luminance provided a static form cue to the target as well as when it did not. Our results have led us to refine our understanding of the conditions under which colour/luminance segregation facilitates the detection of SFM.

2 General methods

2.1 *Subjects*

The two authors, HCL and FK, observed the stimulus. Both had normal colour vision and acuity.

2.2 *Stimuli*

2.2.1 *Generation and display.* The stimuli were generated by a Power Mac 8500/180 with 8 bits-per-gun intensity resolution, and displayed on a 17 inch NEC MultiSync XV17+ RGB video monitor with P22 phosphors. Screen resolution was 640×480 pixels and the frame rate was 120 Hz (noninterlaced). The screen nonlinearity was gamma corrected following calibration of the red and green gun luminances with a UDT photometer. The CIE coordinates of the red and green phosphors were respectively $x = 0.610$, $y = 0.350$, and $x = 0.307$, $y = 0.595$.

2.2.2 *Gaussian micropatterns.* The Gaussian micropatterns were generated by the function:

$$L(x, y) = M + A \exp \frac{-(x^2 + y^2)}{2\sigma^2},$$

where M is mean luminance (which depended on whether the red or green gun was modulated), A is amplitude (50%), and σ is the space constant (0.08 deg). The function was clipped at a diameter of 0.51 deg. Using smoothly varying Gaussian micropatterns rather than conventional hard-edged dots has the advantage that, when containing colour contrast, the amount of chromatic aberration is minimised owing to the removal of high spatial frequencies. Figure 1 shows how the modulations of the red and green guns were combined to produce eight types of Gaussian micropatterns: 'red', 'green', 'bright yellow', 'dark yellow', 'bright red', 'bright green', 'dark red', and 'dark green'. The positions of the micropatterns in each stimulus were random, and when two micropatterns overlapped their red and green modulations (though not DC levels) were separately added. For example if a bright-green Gaussian fell exactly on a dark-red Gaussian the result would be a uniform mid-yellow patch the same as the background. In other words the luminance and colour contrasts of the micropatterns added separately. This was made possible by creating two separate random-dot versions of each stimulus and two separate colour lookup tables (CLUTs). One CLUT made the Gaussians bright red and dark green, the other bright green and dark red. A stimulus consisted of ten apparent-motion frames. Each apparent-motion frame itself consisted of four monitor frames. The first pair of monitor frames displayed two separately generated stimuli which alternated with the two CLUTs. The second pair of monitor frames repeated the first pair. Thus each apparent-motion frame was displayed for 33.3 ms. From now on the Gaussian micropatterns will simply be referred to as 'dots'.

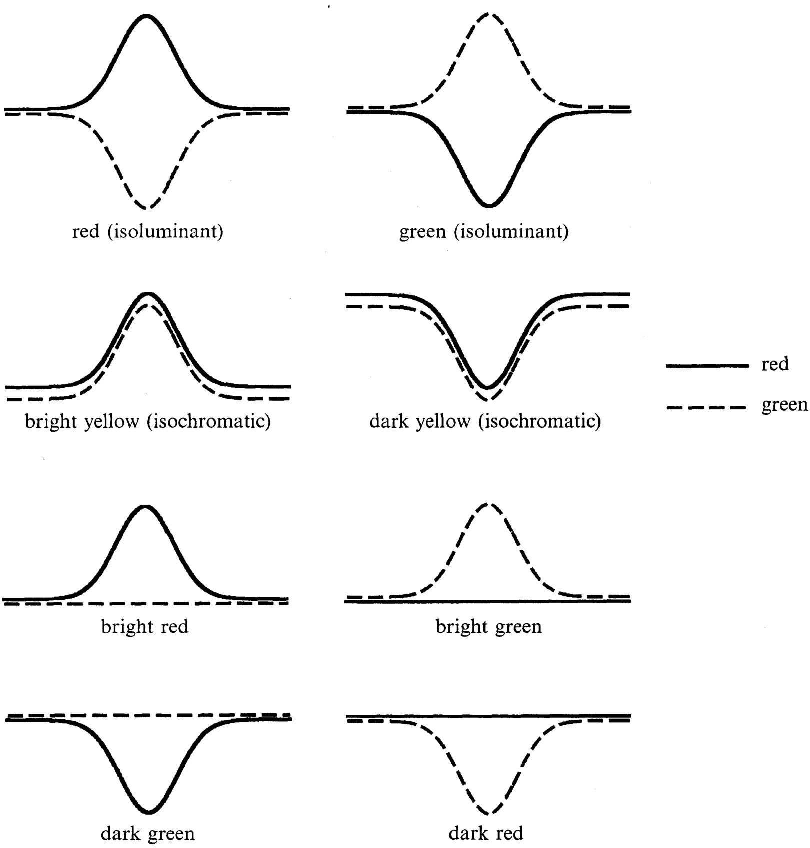


Figure 1. Schematic luminance profiles of the Gaussian micropatterns employed, in terms of their red (solid line) and green (dotted line) phosphor modulations. The *Y*-axis indicates the luminance for each gun.

2.2.2 *Target stimuli (V-shape structure).* The target was a simulated V-shape structure. It was generated with the function

$$Z = aX \text{ (for } x \geqslant 0) \text{ or } Z = -aX \text{ (for } x < 0)$$

when the rotation axis was X, or

$$Z = aY \text{ (for } y \geqslant 0) \text{ or } Z = -aY \text{ (for } y < 0)$$

when the rotation axis was Y, where Z indicates depth and $a = \tan$ (slant). Figure 2 illustrates the schematic diagram of the SFM target when $Z = -aY$ (for $y < 0$). Because parallel projection provides ambiguous depth-ordering information, a simulated V-shape structure can be perceived as convex or concave. Subject HCL mostly saw it as convex whereas subject FK saw it as concave. Neither subject ever perceived a reversal of the target shape during the experiments. Seven levels of slant, between 5° and 75°, were employed to construct a set of target structures. As the slant approached 0°, the V-shape structure became flatter. The rotation speed of the target was fixed at 2° frame^{-1}. The axis and direction of rotation were randomly varied (X-axis or Y-axis, and clockwise or anticlockwise) to minimize subjects' ability to use local motion cues. The moving dots were contained within a stimulus window of 6.8 deg × 6.8 deg at the viewing distance of 57 cm. To prevent observers using static cues to the target such as boundary contours and density gradients, (a) only the central part of the structure was shown through the stimulus window, (b) the lifetime of each dot was limited to either four frames for HCL or five frames for FK, and (c) the number of dots was constrained to be constant regardless of the type of structure and regardless of how much the structure was rotated. In most of the experiments the number of visible dots was fixed at an average of 200. The presentation time of each stimulus was 333 ms (ten apparent-motion frames of 33.3 ms each).

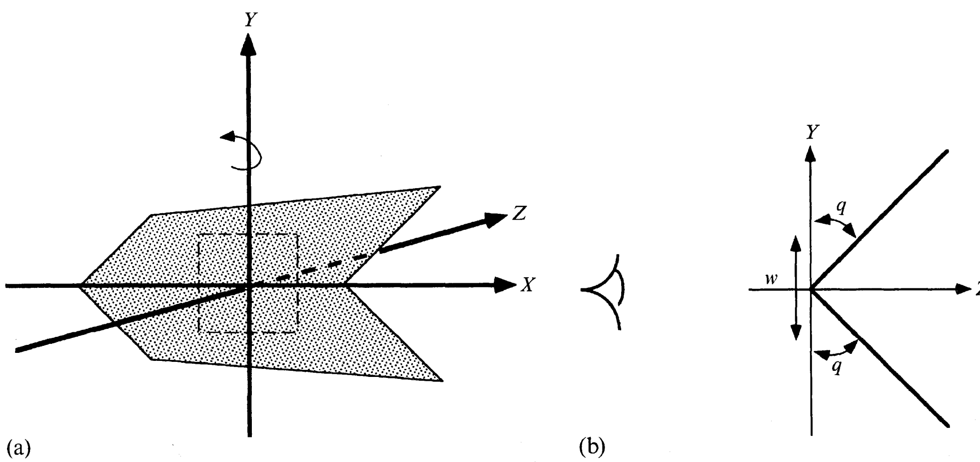
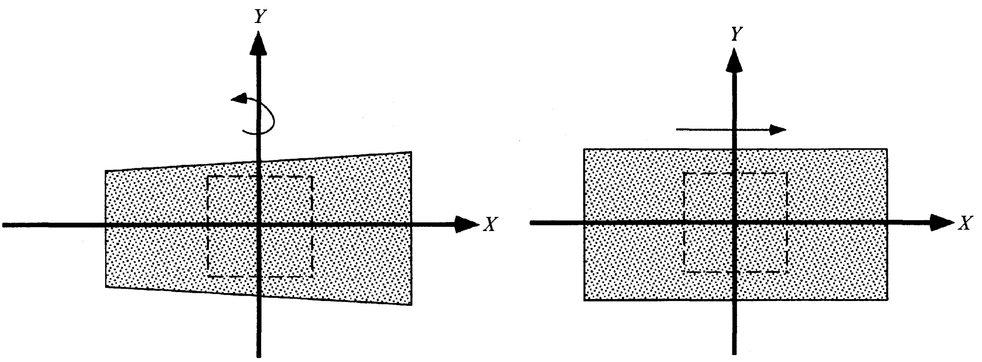


Figure 2. Schematic diagram of a SFM target used in the experiments. (a) The target constructed by the function $Z = -aY$ (for $y < 0$). If the surface were viewed under perspective projection it would appear convex, but under parallel projection it appears either concave or convex. The structure rotates around its Y-axis either clockwise or anticlockwise. The dotted-line square indicates the fixed-size stimulus window. (b) Side view of the target shown in (a) with an observer. q indicates the slant of the target, and w indicates the size of the fixed window, which was 6.8 deg × 6.8 deg. In the view of the observer, the target appears convex in shape.

2.2.3 *Comparison stimuli (flat-surface structures).* Two types of flat-surface comparison stimuli were simulated with parallel projection and are illustrated in figure 3. One rotated around its X-axis or Y-axis, the other translated on its X-axis or Y-axis. Five rotation speeds, 1° frame^{-1} to 6° frame^{-1} (which produced image velocities ranging approximately from 0.051 deg frame^{-1} to 0.299 deg frame^{-1}), and five translation speeds, ranging from 0.034 deg frame^{-1} to 0.238 deg frame^{-1}, were employed. These image velocities covered most of those employed for the target stimuli. The direction of rotation and translation was also randomly varied, clockwise or anticlockwise for rotation direction, and leftward,



(a) (b)

Figure 3. Schematic diagrams of the comparison stimuli. The dotted line indicates the stimulus window. (a) A flat surface rotating around its Y-axis either clockwise or anticlockwise. It may also rotate around its X-axis. (b) A flat surface translating to the right. It may translate to the left, upward, or downward.

rightward, upward, or downward for translation direction. Subjects could not perform the target-detection task just on the basis of 2-D-motion perception, because the comparison stimuli had the same four directions of motion and similar ranges of velocities as the target stimuli. On each trial a target stimulus and comparison were each randomly chosen from their population set. All other stimulus conditions were identical to those of the target.

2.2.4 *Noise.* Random-motion 'noise' was added to both target and comparison stimuli. This was achieved by randomly positioning the noise dots on every stimulus frame.

2.3 *Procedure*

Before each experiment subjects were given plenty of practice to familiarize themselves with the task and achieve near-asymptotic levels of performance. Before each session subjects adapted to a blank yellow screen for 1 min. A fixation cross was provided between stimulus presentations, and subjects were requested not to move their heads. At every trial, a target and two randomly chosen comparison stimuli were presented in random order. The subject observed the stimulus with his dominant eye (the right for both FK and HCL), the nondominant eye being occluded. Each trial was initiated by the response to the previous trial, a keyboard press indicating which interval contained the target. Different tones indicated correct and incorrect responses. Within each session the various levels of target slant were presented in random order, and the number correct for each slant was calculated at the end of each session.

In this study, SFM-detection thresholds were measured in terms of the slant of the V-shape target structure. Why did we not measure detection thresholds in terms of the target-to-noise ratio? Our interest was in whether segregation of target and noise dots by colour/luminance facilitated target SFM detection, and so in the segregated condition we wanted to *completely* segregate target and noise by dot type in order to give this condition its 'best chance'. In the condition in which we eliminated static form cues from the stimulus we also required the target dots to comprise 50% of the total, and so the target-to-noise ratio was thus constrained to be fixed at this level. Therefore it was necessary to manipulate performance other than by varying the target-to-noise ratio.

2.4 *Data analysis*

For each condition the proportion of correct responses, P, was calculated for each target slant. Psychometric functions were fitted by using a Weibull function (Weibull 1951):

$$P = 1 - 0.67\exp[-(c/\alpha)^{\beta}] .$$

The Levenberg–Marquardt algorithm (Marquardt 1963; Press et al 1992) was used to fit the threshold α at the 75%-correct level[(1)] and the slope β so that chi-square was minimized. Goodness of fit at the $p < 0.05$ level was tested by using chi-squares, and every fit was found to be satisfactory. For each subject we performed a statistical test, based on the method employed by Britten et al (1992), to determine whether thresholds for two conditions were significantly different. We compared chi-square values obtained from fitting the data according to two methods. In the first method psychometric functions were fitted individually to the two data sets and the resulting pair of chi-squares summed. In the second method psychometric functions were fitted to the two data sets but with the constraint that the thresholds were equal, and again the two resulting chi-squares were summed. If the difference between the summed chi-squares obtained from the two methods (χ^2_{diff}) exceeded the criterion value (df $= 1$, $p < 0.05$ in chi-square distribution), we concluded that the thresholds for the two conditions were significantly different. When multiple independent statistical tests are performed, one should be conservative about significance of the results, because in multiple tests it is much more probable that one could have significant results by chance. We did not have to worry about this problem, because when the tests were significant in our study the significance level was far from the criterion value.

3 Experiment 1: Detection of SFM as a function of the ratio of red-to-green luminance

We first measured the red-to-green-mean-luminance ratio, $R/(R+G)$ that produced worst detection of SFM. This provided us with an estimate of the 'isoluminant' $R/(R+G)$ value for the task, which we used throughout the rest of the study to minimize the possibility that the chromatic content of the dots would contribute additional luminance components to the stimuli. The stimuli were composed of 100 dots on average, 50% red and 50% green, with no noise distractors. The slant of the target structure was fixed at 45°. For each $R/(R+G)$ value, 96 trials were conducted over three sessions. Figure 4 shows the results. Subjects performed the detection task quite well at low and high values of $R/(R+G)$, while performance dropped to chance level in the middle of the range. A Gaussian function was fitted to estimate the $R/(R+G)$ value producing lowest performance. The continuous function running through the data indicates the fitted function. For HCL this was 0.60, for FK 0.56. These $R/(R+G)$ values were then used throughout the rest of the study.

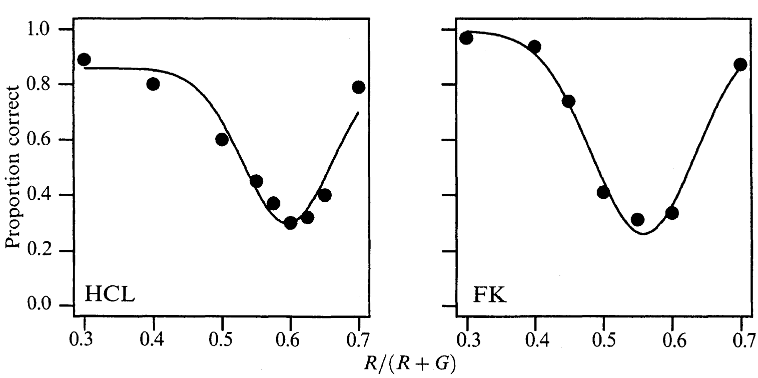


Figure 4. Target detection as a function of $R/(R+G)$, the mean red-to-green-luminance ratio for stimuli made up of red and green dots. The slant of the target was fixed at 45°. Estimated $R/(R+G)$ values producing worst performance were 0.60 and 0.56 for observers HCL and FK, respectively.

[(1)] The Weibull function is $P(c) = 1 - (1-\gamma)\exp[-(c/\alpha)^{\beta}]$, where c is the slant of target structure, γ is guessing rate, α is threshold, and β is slope of the psychometric function. In our three-alternative forced-choice task, the guessing rate was 0.33. The proportion correct at threshold was determined when $c = \alpha$, which is 0.75.

4 Experiment 2: Detection of SFM with and without noise

Our main objective was to test the hypothesis that making the target and noise elements differently coloured facilitated the detection of the structure of the target compared with when target and noise were the same colour. For this hypothesis, however, it is assumed that the addition of noise to the stimulus deteriorates performance in the first place. In this experiment we tested if this assumption was valid. Performance was measured with two different stimulus sets, one with and one without random noise. The number of target and noise dots was approximately 100 each, with the four types of dot—bright red, dark red, bright green, and dark green—distributed in equal proportion. In the condition with added noise, target and noise were not differentiated either by colour or luminance polarity. The slant of the target was varied in both no-noise and noise conditions between 5° and 75°. The results are shown in figure 5. The dotted line and the continuous line are the fitted psychometric functions to the no-noise and noise conditions, respectively. Performance improved with the slant of the target in both conditions, but much more so for the no-noise condition. Thresholds for the no-noise condition were 20.1° and 26.1° for HCL and FK, respectively, and those for the noise condition were 43.5° and 59.8° for HCL and FK. The difference in thresholds between the two conditions is highly significant ($\chi^2_{\text{diff}} = 61.1$, df = 1, $p < 0.05$ for HCL; $\chi^2_{\text{diff}} = 56.7$, df = 1, $p < 0.05$ for FK). These results indicate that perception of SFM was deteriorated when noise was added to the stimulus.

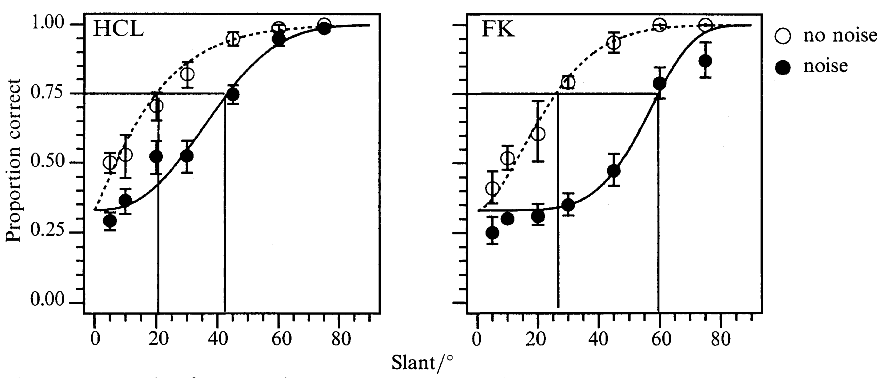


Figure 5. Results for experiment 2. The proportion of correct target detections is plotted as a function of the slant of the target. Open and filled circles are for the no-noise and noise conditions, respectively. The dotted and continuous lines are Weibull fits to the data. The horizontal line intersecting the fitted curves indicates the threshold slant at the 75%-correct level. The number of trials for each data point was 80 for subject HCL and 48 for subject FK. The fitted parameters are as follows. HCL: $\alpha_{\text{no noise}} = 20.1$, $\beta_{\text{no noise}} = 1.15$, $\alpha_{\text{noise}} = 43.5$, $\beta_{\text{noise}} = 2.55$; FK: $\alpha_{\text{no noise}} = 26.1$, $\beta_{\text{no noise}} = 1.65$, $\alpha_{\text{noise}} = 59.8$, $\beta_{\text{noise}} = 5.15$.

5 Experiment 3: Detection of SFM *without* static form cues

The results of experiment 2 demonstrate that the addition of random noise to the stimulus deteriorated performance in detecting SFM. Experiment 3 was designed to test whether making target and noise differently coloured facilitated the detection of SFM. Static form cues were eliminated by using stimuli in which all types of micropattern were present in equal proportion in both 'segregated' (target and noise different in colour composition) and 'unsegregated' (target and noise the same in colour composition) conditions. In both segregated and unsegregated conditions the target-to-noise ratio was always 1.0. Figure 6 shows in schematic form how a flat surface translating to the right was constructed from the four types of dots. Previous studies on the effect of segregating target and noise dots by colour/luminance polarity on perception of 2-D coherent motion have employed just two types of dots, for example red/green dots for colour segregation or

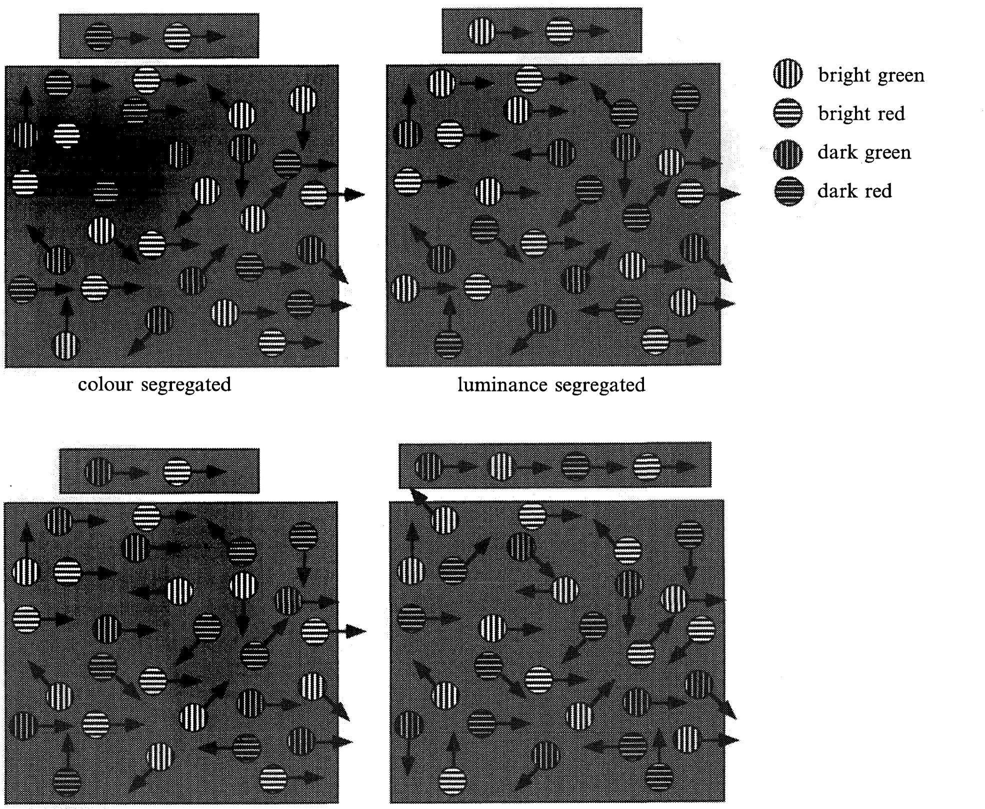


Figure 6. Schematic diagram of the arrangement of dot types used in experiment 3. Equal numbers of the four types of micropattern (bright red, dark red, bright green, and dark green) were present in both segregated and unsegregated conditions, in order to eliminate any static form cues to the target. The dots in the smaller boxes above each panel indicate the target dots. The proportion of target dots was 50%.

dark/bright dots for luminance segregation (Edwards and Badcock 1994, 1996; Croner and Albright 1997). We employed four types of dots, and as a result could test three types of segregated condition, each with its unsegregated comparison condition, by combining the four types of dots appropriately. Each segregated and unsegregated comparison condition employed the same composition of dots. Thus the conditions were (a) colour segregated (bright-red and dark-red dots for the signal, bright-green and dark-green dots for the noise, or vice versa) and unsegregated (bright red, dark red, bright green, and dark green for both signal and noise); (b) luminance segregated (bright-red and bright-green dots for the signal, dark-red and dark-green dots for the noise, or vice versa) and unsegregated; (c) colour-plus-luminance segregated (dark red and bright green for the signal, dark green and bright red for the noise, or vice versa) and unsegregated. Condition (c) is like a conjunction task from the visual-search standpoint (Treisman 1982), and this condition was not tested in previous studies of 2-D motion discrimination. Within each session, segregated and unsegregated conditions were mixed together in random order, and the colour and/or luminance polarity of the target was assigned randomly. Target slant was varied between 10° and 60° for HCL and between 20° and 75° for FK.

The results are shown in figure 7. Detecting the target structure was generally better in the segregated than unsegregated conditions, but the difference was very small and within error range. For subject HCL, the biggest difference was between the luminance-segregated and luminance-unsegregated conditions where thresholds were

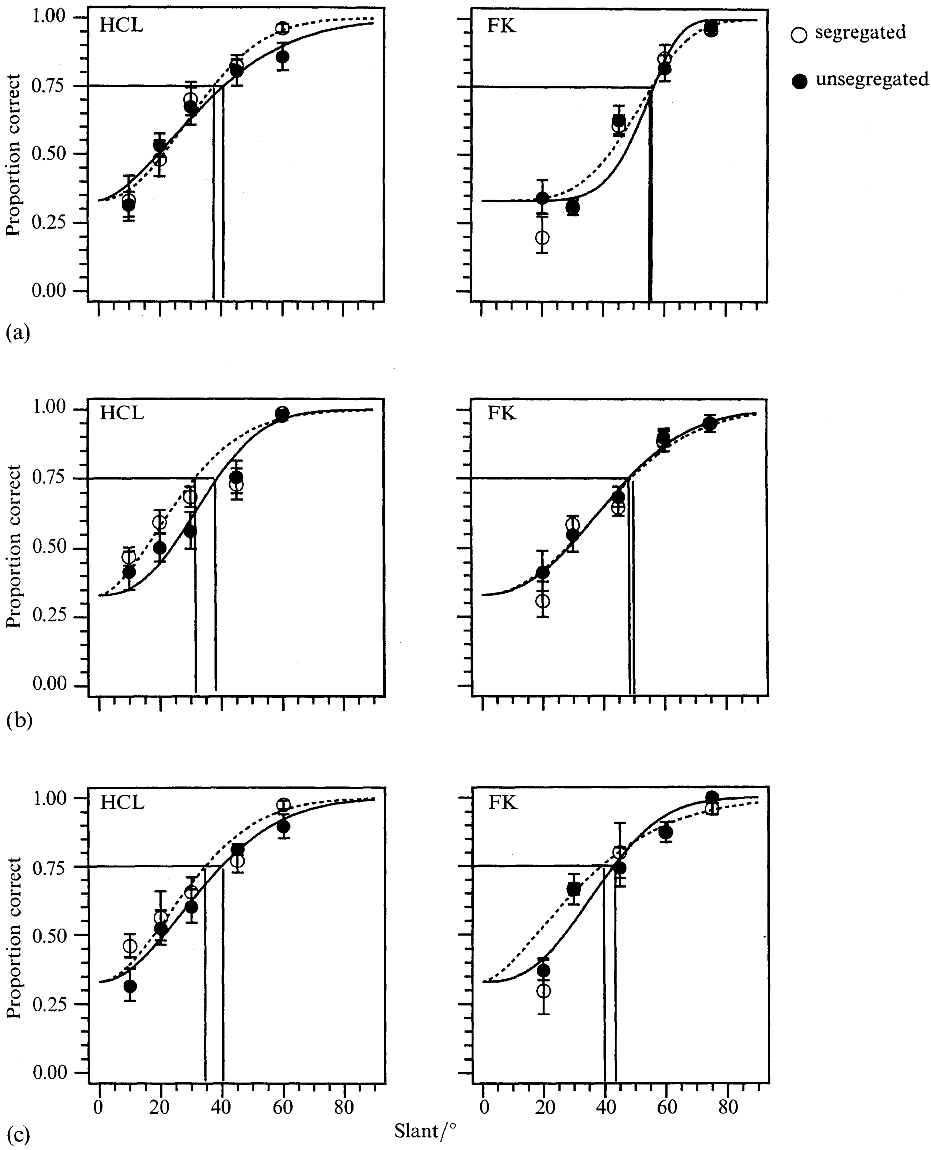


Figure 7. Results for the mixed-colour-and-luminance-dot conditions in experiment 3. Open circles indicate the condition where the target and noise were segregated by colour/luminance polarity while the closed circles indicate the condition where the target and noise were not segregated. The number of trials for each data point was 80 for each subject. The fitted parameters are as follows, with α_{seg} and α_{unseg} thresholds for the segregated and unsegregated conditions, β_{seg} and β_{unseg} for slopes. (a) Colour: for HCL $\alpha_{seg} = 37.8$, $\beta_{seg} = 2.13$, $\alpha_{unseg} = 41.1$, $\beta_{unseg} = 1.66$; for FK $\alpha_{seg} = 55.8$, $\beta_{seg} = 4.18$, $\alpha_{unseg} = 56.4$, $\beta_{unseg} = 6.41$. (b) Luminance: for HCL $\alpha_{seg} = 31.6$, $\beta_{seg} = 1.70$, $\alpha_{unseg} = 39.0$, $\beta_{unseg} = 2.47$; for FK $\alpha_{seg} = 49.4$, $\beta_{seg} = 2.14$, $\alpha_{unseg} = 48.7$, $\beta_{unseg} = 2.27$. (c) Colour and luminance: for HCL $\alpha_{seg} = 34.9$, $\beta_{seg} = 1.83$, $\alpha_{unseg} = 40.2$, $\beta_{unseg} = 1.91$; for FK $\alpha_{seg} = 39.4$, $\beta_{seg} = 1.53$, $\alpha_{unseg} = 43.3$, $\beta_{unseg} = 2.59$.

31.6° and 39.0°, respectively. For subject FK, the biggest difference was between the colour-plus-luminance-segregated and colour-plus-luminance-unsegregated conditions where thresholds were 39.4° and 43.3°, respectively. For both subjects, however, these differences were not significant ($\chi^2_{diff} = 1.70$, df $= 1$, $p > 0.05$ for HCL; $\chi^2_{diff} = 2.99$, df $= 1$, $p > 0.05$ for FK).

We also tested the detection of SFM in the absence of static form cues with isoluminant (colour-contrast-only) and isochromatic (luminance-contrast-only) stimuli. The red and green dots used in the isoluminant stimuli were either segregated or unsegregated into target and noise, and similarly for the bright-yellow and dark-yellow dots used for the isochromatic stimuli. For the isoluminant stimuli, both subjects performed at near chance level for all slants of the target in both segregated and unsegregated conditions, and so results will not be shown here. The results for isochromatic stimuli are shown in figure 8. HCL's thresholds were 27.2° and 23.6° respectively for the segregated and unsegregated conditions, while for FK thresholds were respectively 33.6° and 33.7° for the segregated and unsegregated conditions. Neither difference was significant ($\chi^2_{\text{diff}} = 3.8$, df = 1, $p > 0.05$ for HCL; $\chi^2_{\text{diff}} = 0.28$, df = 1, $p > 0.05$ for FK). We conclude from this experiment that in the absence of static form cues detection of SFM in noise is not facilitated by segregating target and noise by colour and/or luminance polarity.

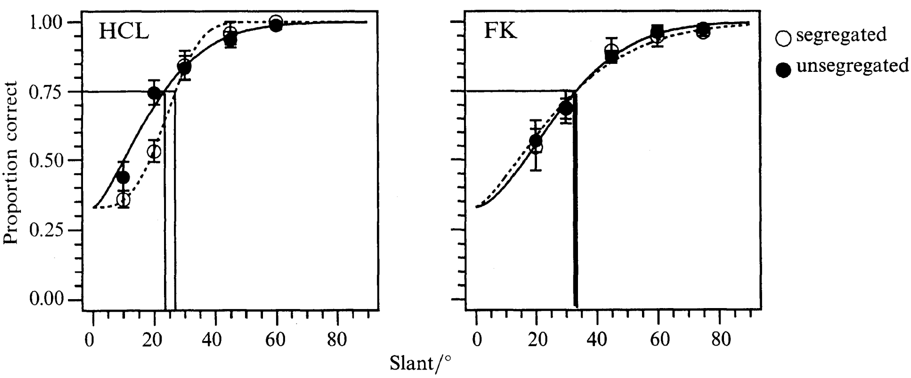


Figure 8. Results for isochromatic conditions in experiment 3. The number of trials for each data point was 80 for each subject, and fit thresholds and fit slope are as follows: for HCL $\alpha_{\text{seg}} = 27.2$, $\beta_{\text{seg}} = 3.24$, $\alpha_{\text{unseg}} = 23.6$, $\beta_{\text{unseg}} = 1.47$; for FK $\alpha_{\text{seg}} = 33.6$, $\beta_{\text{seg}} = 1.43$, $\alpha_{\text{unseg}} = 33.7$, $\beta_{\text{unseg}} = 1.72$.

6 Experiment 4: Detection of SFM *with* static form cues

The results of the previous experiment showed that detection of SFM in noise was *not* facilitated by the segregation of target and noise in the absence of static form cues. Does this imply that colour information is unimportant for the detection of SFM? In this experiment we examined whether the perception of SFM is facilitated when static form cues to the target were introduced via colour differentiation. Static form cues were introduced by making the proportion of target dots only 15% (for HCL) or 20% (for FK). Figure 9 illustrates how this introduces static form cues in the case of a translating flat surface. In the colour-segregated test stimulus two types of dots, bright red and bright green, were always present and segregated into target and noise. The target colour was randomly chosen every trial. The colour-uniform control stimulus was constructed from only bright-yellow dots. The bright-yellow dots in the colour-uniform condition had twice the luminance contrast of the dots (bright red and bright green) in the colour-segregated condition. An alternative stimulus design would have been to give the dots in both conditions the same luminance contrast. However, one could argue that the addition of colour contrast to the dots in the colour-segregated condition increased their salience, thus artifactually favouring this condition. To approximately equate the salience of the dots in both conditions we therefore set equal the sum of luminance contrast and colour contrast of each dot. Target slant was varied in both colour-segregated and colour-uniform conditions between 20° and 75°. Figure 10

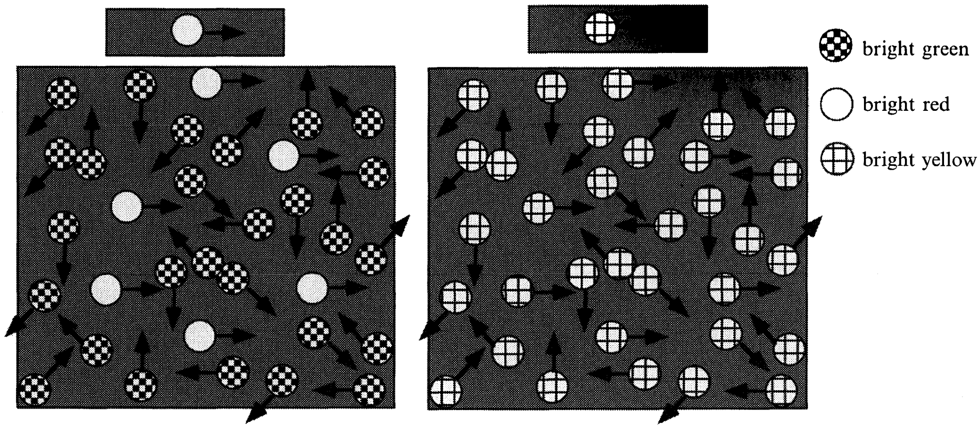


Figure 9. Schematic diagram of the motion stimulus used in experiment 4. In the colour-segregated condition, all target dots were of one colour, either bright red or bright green, and all noise dots were of the opposite colour. The dots in the smaller boxes above each panel indicate the target dots. In the colour-uniform control condition all dots were bright yellow. In both conditions performance was measured as a function of the slant of the target structure.

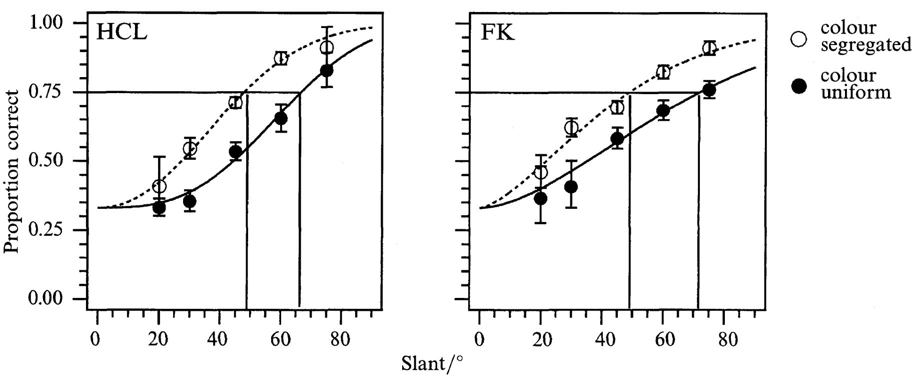


Figure 10. Results for experiment 4 with just two types of micropattern (bright red and bright green) in the colour-segregated condition, and one type (bright yellow) in the colour-uniform condition as illustrated in figure 9. The number of trials for each data point was 80 for each subject. The fitted parameters were as follows (α_{seg} and β_{seg} indicate threshold and slope for the colour-segregated condition, respectively, and α_{uni} and β_{uni} indicate threshold and slope for the colour-uniform condition, respectively): for HCL $\alpha_{\text{seg}} = 48.2$, $\beta_{\text{seg}} = 2.15$, $\alpha_{\text{uni}} = 66.9$, $\beta_{\text{uni}} = 2.99$; for FK $\alpha_{\text{seg}} = 49.3$, $\beta_{\text{seg}} = 1.50$, $\alpha_{\text{uni}} = 72.4$, $\beta_{\text{uni}} = 1.70$.

shows the results. Performance improved with target slant, but much more so for the colour-segregated condition. Thresholds for the colour-segregated condition were 48.2° and 49.3° for HCL and FK, respectively, and those for the colour-uniform condition were 66.9° and 72.4° for HCL and FK, respectively. The difference in thresholds between the two conditions is highly significant ($\chi^2_{\text{diff}} = 13.75$, df $= 1$, $p < 0.05$ for HCL; $X^2_{\text{diff}} = 9.08$, df $= 1$, $p < 0.05$ for FK).

A possible reason for the significant effect of segregation in this experiment other than because static form cues were present is that using two types of dot instead of four produced a relatively simpler stimulus which allowed the effects of segregation to become manifest. We tested this possibility by using stimuli made from four types of dots: bright red, dark red, bright green, and dark green. In the colour-segregated condition, the target was either an equal number of bright-red and dark-red dots, with the noise an equal number of bright-green and dark-green dots, or vice versa. In the colour-uniform condition, an equal number of bright-yellow and dark-yellow dots was present. Again target strength was 15% for subject HCL and 20% for subject FK. Figure 11 shows the results. The effect of the static form cue was again found with the four-dot test stimuli. For the colour-segregated condition, the thresholds were 43.9° and 66.2° for HCL and FK, respectively, while for the colour-uniform condition they were 63.7° and 81.9°, respectively, for HCL and FK. The difference of thresholds between the two conditions was significant for both HCL and FK ($\chi^2_{\mathrm{diff}} = 5.53$, df $= 1$, $p < 0.05$ for HCL; $\chi^2_{\mathrm{diff}} = 7.48$, df $= 1$, $p < 0.05$ for FK). The results of these experiments show that when static form cues are introduced via colour segregation, detection of SFM in noise is facilitated, and regardless of whether the stimulus is composed of two or four types of dots. Although we have not explicitly tested analogous luminance-segregated and colour-and-luminance-segregated conditions, it is reasonable to expect that one would obtain similar results.

The psychometric functions in figures 10 and 11 (static form cues present) are shifted to the right compared with those in figure 7a (no static form cues). This was almost certainly due to the different target-to-noise ratios in the stimuli, 50% as opposed to 15% (HCL) and 20% (FK).

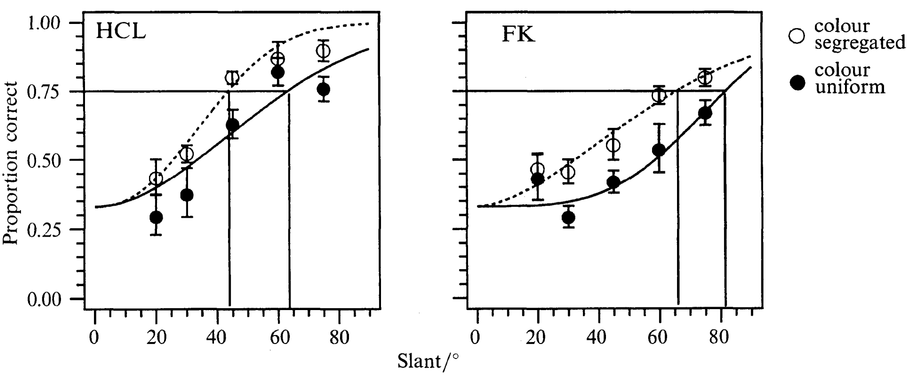


Figure 11. Results for experiment 4 with four types of micropattern (bright red, dark red, bright green, and dark green) in the colour-segregated condition and two types of micropattern (bright yellow and dark yellow) in the colour-uniform condition. All symbols and the number of trials for each data point are the same as in figure 10. Fitted parameters are as follows: for HCL $\alpha_{\mathrm{seg}} = 43.9$, $\beta_{\mathrm{seg}} = 2.28$, $\alpha_{\mathrm{uni}} = 63.7$, $\beta_{\mathrm{uni}} = 1.92$; for FK $\alpha_{\mathrm{seg}} = 66.2$, $\beta_{\mathrm{seg}} = 1.72$, $\alpha_{\mathrm{uni}} = 81.9$, $\beta_{\mathrm{uni}} = 3.71$.

7 Experiment 5: Effect of selective attention

The results of the previous experiments have shown that, whereas differentiating target and noise by colour/luminance facilitated detection of SFM when static form cues to the target were present, no facilitation was found when static form cues were absent. It is quite possible that the latter negative result was due to the subjects not knowing on each trial which type, or types, of micropattern were target and which were noise. What would happen, however, if they did have this information, and were thus able to selectively attend to the target? We tested this by comparing performance between two classes of condition. In the first, 'attention-plus-segregated', condition the target dots were segregated along the chosen dimension, and observers knew the colour or luminance polarity of the target dots prior to the session, which remained constant throughout. In the second, 'unsegregated' condition the dots were unsegregated, and thus attention to any one dot type would not confer any advantage. Static form cues were eliminated from both classes of condition by making target and noise dots equal in number. The colour-segregated conditions were subdivided into four subconditions:

(a) dark-red target – dark-green noise; (b) dark-green target – dark-red noise; (c) bright-red target – bright-green noise; (d) bright-green target – bright-red noise. The both-segregated conditions were subdivided into (a) bright-green target – dark-red noise; (b) dark-red target – bright-green noise; (c) bright-red target – dark-green noise; (d) dark-green target – bright-red noise. For the luminance-segregated condition we used only an isochromatic stimulus, which was subdivided into two subconditions: (a) dark-yellow target – bright-yellow noise; (b) bright-yellow target – dark-yellow noise. The corresponding unsegregated comparison conditions involved the same types of dot as in the segregated conditions, but divided equally between target and noise. This resulted in a total of fifteen conditions: four colour-segregated and two colour-unsegregated conditions, four both-segregated conditions and two both-unsegregated conditions, two isochromatic luminance-segregated conditions, and one isochromatic luminance-unsegregated condition. The slant of the target was varied between 20° and 75° for HCL, and between 5° and 75° for FK.

The proportions of correct responses in the subconditions of each attention-plus-segregated and each unsegregated condition were averaged for each slant of the target. The results are shown in figure 12 (see over), and the values for χ^2_{diff} and p for each condition are provided in table 1. For both subjects there was some advantage for some of the attention-plus-segregated conditions, but none of the conditions from either subject produced any significant difference between attention-plus-segregated and unsegregated conditions. This result implies that prior knowledge of the target in the segregated conditions does not result in a significant superiority of the segregated over unsegregated stimuli.

Table 1. The χ^2_{diff} obtained from experiment 5.

Observer	Colour segregated vs colour unsegregated	Both segregated vs both unsegregated	Isochromatic luminance segregated vs isochromatic luminance unsegregated
HCL	$\chi^2_{\text{diff}} = 0.58$, df = 1 $p > 0.05$	$\chi^2_{\text{diff}} = 1.10$, df = 1 $p > 0.05$	$\chi^2_{\text{diff}} = 3.50$, df = 1 $p > 0.05$
FK	$\chi^2_{\text{diff}} = 0.25$, df = 1 $p > 0.05$	$\chi^2_{\text{diff}} = 2.25$, df = 1 $p > 0.05$	$\chi^2_{\text{diff}} = 3.45$, df = 1 $p > 0.05$

8 Discussion

The primary aim of this study was to test whether detection of SFM in noise was facilitated when target and noise were differentiated in colour, luminance polarity, or both, under conditions in which there were no static form cues to the target. Our results indicate that it was not. It would appear that the mechanisms involved in SFM do not automatically group together local features with similar properties along the colour/luminance dimension. This is an interesting finding, if one considers that objects in natural scenes often differ from their backgrounds by colour/luminance. One might have expected the motion system to exploit this fact, even when the target did not 'pop out' from the background by virtue of its different colour/luminance. We showed, however, that static form cues were necessary for SFM processing to benefit from colour/luminance segregation. In recent neurophysiological studies, Albright (1992) and Stoner and Albright (1993) suggested that 2-D-motion-integrative mechanisms are 'form-cue invariant'. They showed that neurons in primate area MT, which are centrally involved in motion processing, are blind to the particular form of the moving targets they detect. Our results with SFM detection are consistent with these findings.

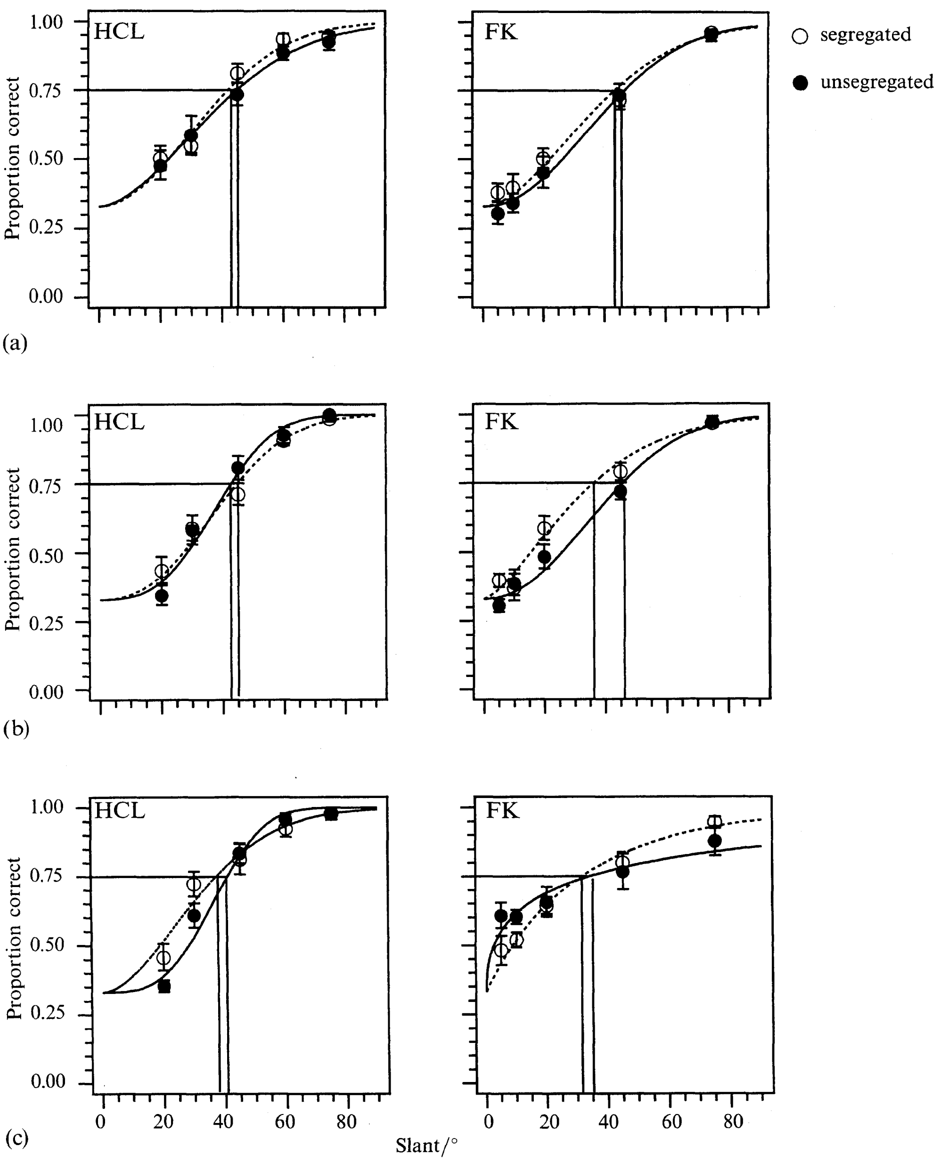


Figure 12. Results for experiment 5 in which the effect of selective attention to the target was investigated. The number of trials for each data point was 160 for each subject, and the symbols are the same as in figure 7. (a) Colour: for HCL $\alpha_{\text{seg}} = 42.3$, $\beta_{\text{seg}} = 1.98$, $\alpha_{\text{unseg}} = 45.3$, $\beta_{\text{unseg}} = 1.78$; for FK $\alpha_{\text{seg}} = 43.6$, $\beta_{\text{seg}} = 1.81$, $\alpha_{\text{unseg}} = 46.9$, $\beta_{\text{unseg}} = 2.13$. (b) Colour and luminance: for HCL $\alpha_{\text{seg}} = 45.0$, $\beta_{\text{seg}} = 2.41$, $\alpha_{\text{unseg}} = 43.0$, $\beta_{\text{unseg}} = 2.95$; for FK $\alpha_{\text{seg}} = 36.6$, $\beta_{\text{seg}} = 1.44$, $\alpha_{\text{unseg}} = 46.1$, $\beta_{\text{unseg}} = 2.12$. (c) Isochromatic luminance: for HCL $\alpha_{\text{seg}} = 37.5$, $\beta_{\text{seg}} = 1.78$, $\alpha_{\text{unseg}} = 41.1$, $\beta_{\text{unseg}} = 3.27$; for FK $\alpha_{\text{seg}} = 32.0$, $\beta_{\text{seg}} = 0.96$, $\alpha_{\text{unseg}} = 35.2$, $\beta_{\text{unseg}} = 0.47$.

For tasks involving discrimination of the direction of 2-D motion, contradictory results have been reported for the effect of target–noise segregation by colour and/or luminance polarity. Edwards and Badcock (1994, 1996) found that the addition of noise dots deteriorated motion discrimination by the same amount irrespective of whether their colour/luminance was the same as or different from that of the target dots. Croner and Albright (1997), on the other hand, showed that segregation of target and noise dots by colour/luminance dimension facilitated motion discrimination. The different results almost certainly reflect the differences in stimulus design between the two studies.

In the Croner and Albright study target and noise dots were completely segregated by colour and, because there were less than 5% of target dots present at threshold, the target would clearly stand out in a stationary view of the stimulus. In the Edwards and Badcock study, on the other hand, although all the dots which were different in type from the signal were noise dots, many noise dots were the same type as the signal and therefore the signal dots would not be so clearly differentiated in a stationary view of the stimulus. Thus the suggestion made here that static form cues must be introduced when target and noise are segregated by dot type in order that motion perception is facilitated is one way of resolving the discrepancies in these previous studies. A recent study by us on 2-D-motion-direction discrimination supports this conclusion (Li and Kingdom 1998).

Are our results with SFM simply a reflection of processes involved either in velocity discrimination or in solving motion correspondence? We argue not. Although when target slant increased the average velocity of the target dots increased, the population of comparison stimuli contained the same range of dot velocities as those of the target stimuli. Moreover, all the target stimuli reflected the same level of difficulty in achieving motion correspondence. Last, subjects reported that they performed the task on the basis of the 3-D shape of the targets.

How can the effect of static form cues in SFM be explained? One might suppose that with static form cues one could selectively attend to the target. Research has shown that the perception of 3-D structure may be influenced by higher-level factors such as visual attention (Epstein and Lovitts 1985; Hochberg and Peterson 1987; Shulman 1991). However, it is also possible that static form cues operate preattentively, so that 'knowing' the colour or luminance polarity of the target dots and attending to them is not necessary. We tested this idea in experiment 5, in which static form cues were eliminated from the stimulus, but in which subjects knew the colour or luminance polarity of the target dots for each segregated condition prior to each session and were, moreover, instructed to consciously attend to them. Yet no significant difference was found between the segregated and unsegregated conditions. This does not, of course, imply that SFM mechanisms are not in any way affected by attention. Rather, it implies that attention is not involved in the initial segmentation of the image.

Why is motion processing form-cue invariant? One possible answer is that there is simply no good reason why the visual system should automatically group similarly coloured features when processing their motion properties. If an object is multicoloured, separately processing the different-coloured components of the object would require integrating a number of separate colour-labelled motion maps in order to determine the 3-D structure of the object as well as its motion properties. This would be time consuming and require much neural hardware, and be less efficient than if colour was simply ignored and the visual system instead concentrated on integrating those attributes which were common to all parts of the object, ie its motion. If, on the other hand, an object was clearly differentiated from its background, for example if it was defined by relatively few differently coloured elements, then it would make sense for the visual system to first segregate the object from its surround before establishing its motion properties.

9 Conclusion

The perception of SFM in noise does not necessarily benefit from target and noise being differentiated by colour and/or luminance polarity. Only when the form of the target is revealed by such differentiation in the stationary view of the image does SFM perception appear to benefit. In the absence of static form cues, colour/luminance differences between objects in natural scenes probably do not provide a sufficiently reliable basis for segmentation, and as a result the visual system prefers to pool motion information across all colour/luminance differences when establishing the 3-D structure of the object.

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