PERGAMON

Vision Research 41 (2001) 3873–3882

Vision Research

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Motion-surface labeling by orientation, spatial frequency and luminance polarity in 3-D structure-from-motion

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Received 31 August 2000; received in revised form 31 July 2001

Abstract

A compelling percept of three-dimensionality is attainable from a purely motion-defined simulation of a transparent rotating cylinder, referred to as 3-D structure-from-motion (SFM). Interestingly, subjects rarely perceive reversals of the cylinder's direction of rotation when they are introduced. Treue, Andersen, Ando, and Hildreth (Vision Res. 35 (1995) 139–148) have argued that this reflects the visual system's insensitivity to the textural detail on the cylinder's motion surfaces. We have recently shown however that with cylinders made from oriented micropatterns, motion reversals are perceived when the orientations of the micropatterns are different on the cylinder's front/back surfaces, suggesting that the visual system is sensitive to the *type* of feature in these stimuli (Vision Res. 39 (1999) 881–886). In the present study we extended this finding by testing for feature-sensitivity along other dimensions besides orientation, specifically spatial frequency, colour and luminance polarity. We found that subjects perceived more rotation direction reversals when the front/back surfaces of the cylinder were segregated, as opposed to non-segregated by feature-type, along all of these dimensions except, notably, colour. We also investigated the stage at which the feature-sensitivity is incorporated in 3-D SFM. We reasoned that if 3-D SFM mechanisms were tuned, or labeled for feature-type, swapping of features during the cylinder's rotation would result in *illusory* reversals in just the feature-segregated condition, whereas if grouping of like-features preceded the formation of 3-D motion surfaces, no such illusory reversals would be expected. We found that feature-swapping resulted in more illusory reversals in the feature-segregated compared to non-segregated conditions, supporting the mechanism tuning, or labeling, hypothesis. © 2001 Published by Elsevier Science Ltd.

Keywords: Labeling; Motion-surface; Structure-from-motion

1. Introduction

A compelling percept of 3-D (three dimensional) structure can be obtained from displays which simulate the motion properties of objects, but in which all other depth cues, such as stereopsis and perspective, have been eliminated (Braunstein, 1962; Rogers & Graham, 1979; Todd, 1984; Ullman, 1984; Wallach & O'Connell, 1953). Such a percept is referred to as '3-D structure-from-motion' or the 'kinetic depth effect'. A well-studied 3-D structure-from-motion (SFM) stimulus is a rotating cylinder, or sphere, comprised of moving random dots, simulated with parallel projection (Andersen & Braunstein, 1983; Braunstein, Andersen, & Riefer, 1982; Jiang, Pantle, & Mark, 1998; Nawrot & Blake, 1989; Treue, Andersen, Ando, & Hildreth, 1995; Treue, Husain, & Andersen, 1991). A schematic version of the cylinder stimulus is shown in Fig. 1. Subjects easily perceive a rotating, rigid, transparent 3-D-cylinder, though the cylinder's perceived direction of rotation is not stable and observers occasionally perceive its direction reverse, a phenomenon called 'spontaneous reversal' (Johansson, 1964; Nawrot & Blake, 1989, 1991). Spontaneous reversals result from the inherent ambiguity of the depth relationship between the cylinder's front and back surfaces, as with the well-known Necker cube.

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0042-6989/01/$ - see front matter © 2001 Published by Elsevier Science Ltd.
PII: S0042-6989(01)00227-9

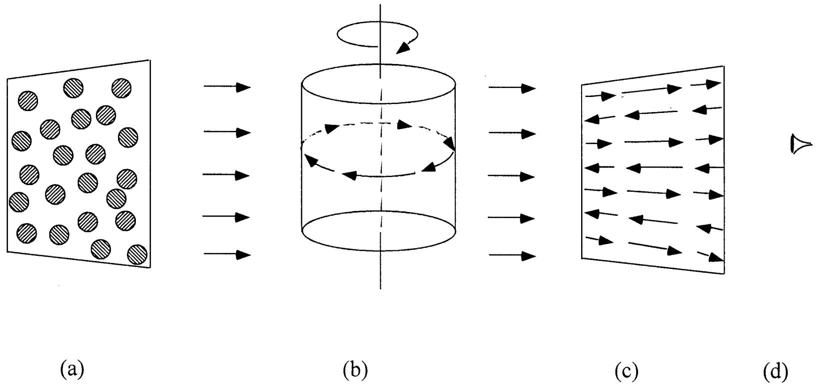

Fig. 1. Schematic representation of a rotating cylinder simulated by parallel projection. (a) the Gabor (or Gaussian) micropatterns are randomly plotted on a 2-D square; and (b) projected onto a rotating cylinder with two transparent surfaces; (c) shows the resulting stimulus as seen by the observer (d).

Recently, Treue et al. (1995) reported the interesting observation that in cylinders simulated with parallel projection, subjects rarely perceived reversals that were *physically introduced* by reversing the 2-D direction of dots. This is surprising considering that observers perceive spontaneous reversals even when none are there. Treue et al. argued that subjects rarely perceived introduced rotation reversals because 3-D SFM mechanisms only represent the *surfaces* of the cylinder via a process of surface interpolation, and not the specific *arrangement* of surface dots. In other words 3-D SFM mechanisms are insensitive to textural detail.

Although the results of Treue et al. suggest that the arrangement of features was not represented in 3-D SFM, an important question remained as to whether the *type* of feature was nevertheless represented. Suppose, for example, the front and back surfaces of a simulated transparent cylinder comprised different *types* of feature. Would the visual system be insensitive to such feature differences, and continue to miss physically existing rotation reversals? Li and Kingdom (1999) addressed this question using a simulated transparent cylinder made from moving Gabor micropatterns. There were two conditions. In the 'segregated' condition the Gabors on the front and back surfaces of the cylinder were different in orientation (e.g. 90° vs. 0°), whereas in the 'non-segregated' condition both surfaces comprised Gabors of both orientations (e.g. 90° and 0°). Subjects perceived many more introduced rotation reversals in the segregated condition. Moreover, in the segregated condition, the proportion of perceived rotation reversals increased systematically with the difference in micropattern orientation between the two motion surfaces, whereas in the non-segregated condition the magnitude of orientation difference had no effect on reversal rates. Li and Kingdom argued that the visual system must be sensitive to at least some types of featural information in the perception of motion surfaces. An important question that remains is what other types of feature besides orientation are salient for 3-D SFM mechanisms. The first purpose of the present study is to consider whether differences in the luminance-polarity, spatial frequency and colour of the micropatterns making up the two surfaces of a SFM cylinder facilitates the perception of rotation reversals. The method for this part of the study was to introduce rotation reversals into the stimulus (see Fig. 2a), and ask subjects to report whenever they were perceived.

Our second purpose is to determine whether the feature sensitivity revealed in the Li and Kingdom (1999) study shows that 3-D SFM mechanisms are tuned to specific features, or whether it is best understood in terms of grouping processes that precede the analysis of 3-D SFM. Prior grouping of similar features might facilitate the detection of rotation reversals simply by making the front and back surfaces of the 3-D SFM object more distinct, even if 3-D SFM mechanisms were themselves blind to feature type. These two alternative hypotheses are illustrated in Fig. 3.[1]

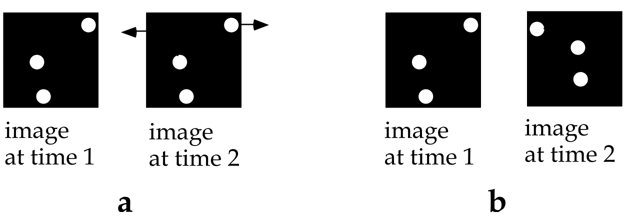

Fig. 2. Schematic representation of the paradigms used in the two experiments. (a) Experiment 1: rotation reversals were introduced by reversing the direction of motion of the micropatterns. (b) Experiment 2: features were swapped while keeping motion direction constant.

[1] It is conceivable that feature grouping might occur after the 3-D representation is formed. Our primary concern however is to distinguish between feature grouping and surface labeling/tuning, and so the precise stage at which feature grouping takes place is not important.

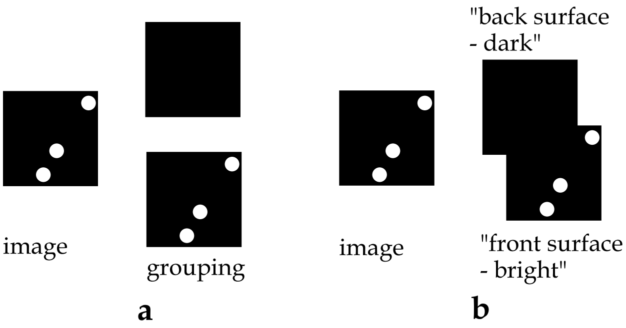

Fig. 3. Schematic representation of two hypotheses concerning the effects of 'feature-swapping': (a) like-features are automatically grouped prior to the formation of the 3-D object representation (e.g. bright dots vs. dark dots); (b) the motion surfaces are labeled by feature-type (here, luminance polarity) providing a linkage between the feature-type and 3-D depth of the surfaces (e.g. 'dark' = back-surface vs. 'bright' = front-surface).

In order to determine whether feature information is incorporated before or at the stage of motion-surface generation, we have employed a manipulation whereby the features on the two surfaces are periodically swapped as the cylinder rotates (see Fig. 2b). For example, if the feature of interest is luminance polarity, all micropatterns are periodically swapped in luminance polarity from, say, bright to dark or vice versa, while keeping the rotation direction unchanged. There are no introduced rotation reversals with this technique, only feature swappings, and thus any perceived reversals are illusory. We suggest that such illusory reversals are likely to occur in the feature-segregated condition only if the cylinder's motion surfaces are tuned, or labeled for feature-type (e.g. dark = 'back-surface-moving-leftward'; bright = 'front-surface-moving-rightward'). If grouping of like-features occurs prior to the formation of the cylinder's motion surfaces, there seems no reason why feature swapping per se should influence the cylinder's perceived direction of rotation. A possible counter-argument to using feature swapping as a test for mechanism-tuning is that feature swapping might disrupt the processes which segment, or label, the front and back surfaces of the cylinder, even after the 3-D object representation has been fully formed, producing illusory rotation reversals unrelated to mechanism tuning. For this reason we have included a control 'feature-non-segregated' condition, in which both the front and back surfaces comprise a mixture of the two features (e.g. bright and dark dots in both surfaces). If feature swapping disturbs the perception of motion direction itself, then the same amount of illusory rotation reversals should be observed in the feature-non-segregated as in the feature-segregated condition.

The experiments we have conducted are as follows. We first seek to confirm our previous result that micropattern orientation is a salient feature for 3-D SFM processing, by comparing the proportion of perceived reversals between feature-segregated and -non-segregated conditions (Fig. 2a). Using the same method we consider whether micropattern spatial frequency, luminance polarity and colour are also salient for perceiving rotation reversals. A control experiment compares the number of *spontaneous* illusory reversals between feature-segregated and -non-segregated conditions. Second we compare the number of illusory rotation reversals between feature-segregated and -non-segregated conditions when the features on the front/back motion surfaces are periodically swapped (Fig. 2b).

2. Experiment 1

The aim of Experiment 1 is first to confirm the previous findings of Li and Kingdom (1999) that more motion reversals are perceived when the micropatterns on the front and back surfaces of the cylinder differ in orientation. The second purpose is to test whether differences in micropattern spatial frequency, luminance polarity and colour have similar effects.

2.1. Methods

2.1.1. Subjects

One of the authors, HL, acted as an observer. The two other subjects, AW and JL were undergraduate volunteers who were naive as to the purpose of the experiments. All subjects had normal vision.

2.1.2. Stimuli

2.1.2.1. Display generation. The stimuli were generated by a PowerMac 8500/180 with 8 bits-per-gun intensity resolution, and displayed on a 17-inch NEC MultiSync XV17 + RGB video monitor (640 H × 480 V pixel resolution; P22 phosphors; 120 Hz frame rate). The screen nonlinearity was gamma-corrected following calibration of the three gun luminances with a Universal photometer (Optikon).

2.1.2.2. Micropatterns. Two kinds of micropatterns were employed: Gaussians and Gabors. The Gaussians were used to examine the effects of luminance polarity and colour. The Gabor micropatterns were used to examine the effects of orientation and spatial frequency. Gaussians and Gabors were generated using the following functions:

$$L(x, y) = M + A \exp[-(x^2 + y^2)/(2\sigma^2)],$$

$$L(x, y) = M + A \exp[-(x^2 + y^2)/(2\sigma^2)] \times \sin\{2\pi f[x^2\cos(\theta) + y^2\sin(\theta)]\},$$

where M is mean luminance of 37.4 cd/m^2, A amplitude of 0.5, σ the space constant of 0.076°, f spatial frequency of 3.3 or 5.6 cd, and θ the orientation of the carrier, either $-45°$ or $+45°$. The functions were clipped at a diameter of 0.34°. The phase of each Gabor was set to make it odd-symmetric, ensuring that the Gabor's mean luminance was the same as that of the background. When two micropatterns overlapped, their amplitudes but not DC levels were added. For the orientation, spatial frequency and luminance polarity conditions a conventional black–white display was employed, with a background luminance of 37.4 cd/m^2. For the luminance polarity condition, the luminance of the dark Gaussian micropatterns ranged from 0.3 cd/m^2 to the background level. For the bright Gaussians, the luminance ranged from the background level to 74.5 cd/m^2. Both types of Gaussian had a Weber contrast of 0.99. Viewing distance was 57 cm.

2.1.2.3. Colour Gaussians. For the colour condition, a red–green–yellow display was employed. Fig. 4 shows how the modulations of the red and green guns were combined to produce two types of Gaussian micropatterns: 'bright red' and 'bright green'. The background was yellow, the average of 'red' and 'green'. As with all stimuli, the positions of the micropatterns were random, and when two micropatterns overlapped their red and green modulations (though not DC levels) were separately added (i.e. red with red, green with green). The CIE coordinates of the red and green phosphors were, respectively $x = 0.610$, $y = 0.350$, and $x = 0.307$, $y = 0.595$.

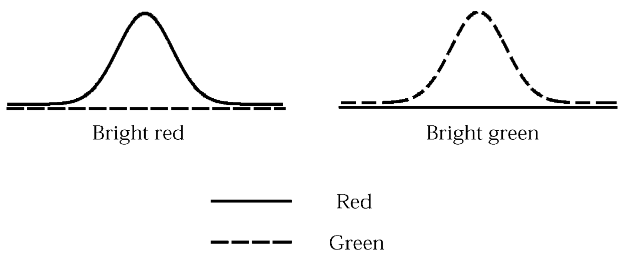

Fig. 4. Schematic luminance profiles of Gaussian micropatterns employed in the colour experiments, in terms of their red (solid line) and green (dotted line) phosphor modulations. The Y-axis indicates the luminance for each gun.

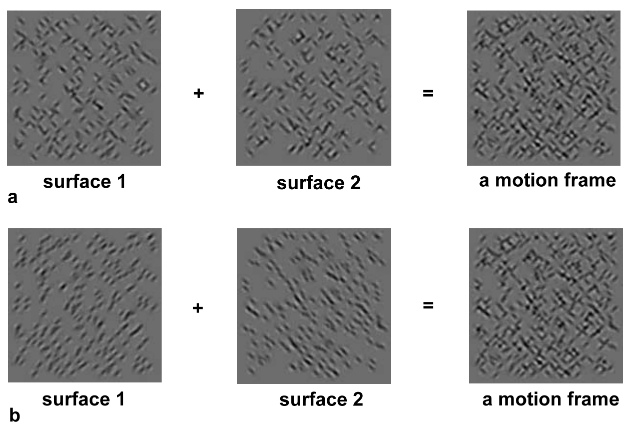

Fig. 5. 2-D view of the $+45°$ and $-45°$ micropattern conditions. (a) Non-segregated condition in which two transparent surfaces were not differentiated by micropattern orientation. (b) Segregated condition in which two transparent surfaces were differentiated by micropattern orientation. There was no difference between the stationary frames of the two conditions.

Although our coloured micropatterns were deliberately non-isoluminant, we wanted to ensure that they were nevertheless equally luminous, so that there were no differences in luminance contrast that could facilitate segmentation. To do this we measured the isoluminant red-to-green-mean luminance ratio, $R/(R+G)$, for the SFM task using the criterion of worst perceived SFM. Subjects adjusted the $R/(R+G)$ ratio until the percept of a rigid rotating 3-D cylinder was minimised. Each subject made 10 adjustments. The average $R/(R+G)$ was 0.60 for HL, 0.54 for AW and 0.56 for JC.

2.1.2.4. Simulated rotating cylinder. A transparent rotating cylinder was simulated using parallel projection, that is without perspective cues. Fig. 1 illustrates the stimulus construction. The radius of the cylinder was 3.4° and its height 6.8°. The rotation speed was 3°/frame or 90°/s. The number of micropatterns presented in each motion frame was 400 (200 for each surface). The stimulus comprised 400 motion frames, with each motion frame consisting of four repeated frame buffers (monitor frames) of 33.3 ms each. For the first motion frame the positions of the dots were randomly assigned so that dot density was uniform. Normally, if the dots were translated continuously, the sides of the cylinder would become more dense as the dots slowed down near the cylinder's edge. To make dot density as uniform as possible across the whole cylinder, and to avoid subjects tracking a dot, each dot had a finite lifetime of 167 ms, or five motion frames, after which the micropattern reappeared elsewhere at a random position in the stimulus. Total stimulus presentation time was 13.32 s (400 frames $\times$ 33.3 ms = 13.32 s). In Experiment 1 eight rotation reversals (i.e. all micropatterns reverse their 2-D directions, see Fig. 2a) were physically introduced during each stimulus presentation. The time of each reversal was randomized with the following two constraints: (1) the first and the last reversals were not introduced during the first and last second; (2) the interval between consecutive reversals was a minimum of 500 ms.

The transparent surfaces of the cylinder could be either segregated or non-segregated in terms of micropattern orientation, spatial frequency, luminance polarity or colour. In the segregated condition, one surface comprised one type of micropattern, the other surface its complement (e.g. if micropattern orientation, $-45°$ and $+45°$; spatial frequency, 3.3 and 5.6 cd; luminance polarity, dark and bright; colour, red and

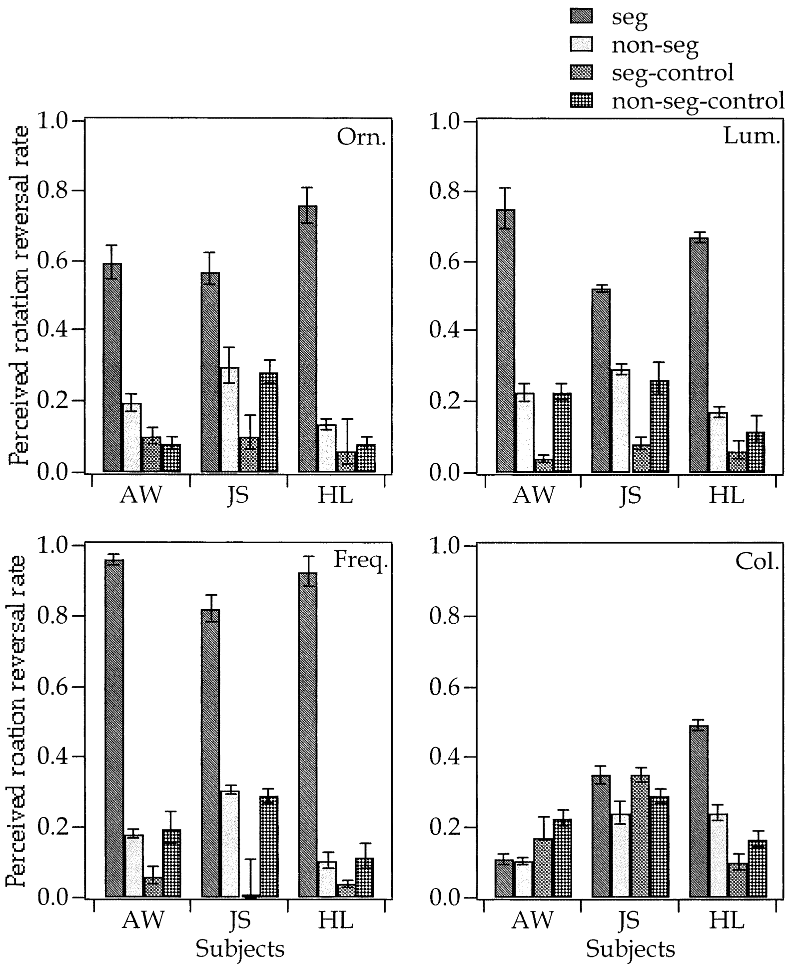

Fig. 6. Results for Experiment 1 for three subjects. The proportion of perceived rotation reversals for physically introduced reversals is shown for both feature-segregated ('seg') and feature-non-segregated ('non-seg') conditions. 'seg-control' and 'non-seg-control' are the results for spontaneous reversals. The four panels show the results for the four feature-types: orientation (Orn.), luminance (Lum.), spatial frequency (Freq.), and colour (Col.). Error bars are standard errors.

green). In the non-segregated condition, both surfaces contained both types of micropattern in equal proportions. Fig. 5 shows schematically the segregated and non-segregated stimuli in the orientation condition.

2.1.3. Procedure

Experiment 1 comprised four separate blocks and each feature-type was examined in a separate block. Before the experiment, subjects were given enough practice to familiarize themselves with the task and achieve near-asymptotic levels of performance. Before each session, subjects adapted to a blank gray (or yellow for the colour condition) screen for 1 min. On every trial, a stimulus randomly chosen from one of the segregated or non-segregated stimulus sets was presented, and subjects were instructed to press a key every time they perceived the direction of rotation reverse. There were eight introduced reversals during each stimulus presentation. The subject observed the stimulus with his/her dominant eye, the non-dominant eye being occluded. The inter-trial interval was about 5 s. Each stimulus was presented three times in random order during each session, and there were three sessions (i.e. nine trials per experimental condition), resulting in a total of 72 physical rotation reversals per condition. In the control experiment, which measured the rate of perceived spontaneous reversals, no physical rotation reversals were introduced. The proportion of perceived reversals across the three sessions was calculated for each condition. In order to relate the number of spontaneous reversals to the other conditions, the rate of spontaneous reversals was defined as the total number of spontaneous reversals expressed as a fraction of 72 (the total number of physical reversals in Experiment 1 or feature-swaps in Experiment 2). The proportion of perceived rotation reversals was measured for both segregated and non-segregated conditions.

2.2. Results

Fig. 6 shows the proportion of perceived rotation reversals for physically introduced reversals, as well as the rate of spontaneously perceived reversals, for three subjects. Because spontaneous reversals occasionally occur, it was necessary to have an estimate of their rate of occurrence in both the segregated and non-segregated conditions, in order to be sure that any differences between conditions with introduced reversals were not due to differences in spontaneous reversal rates. With introduced reversals, all three subjects perceived significantly more reversals when the two surfaces of the cylinder were segregated by micropattern orientation, spatial frequency or luminance polarity (for orientation, $F(1, 2) = 27.463$, $P < 0.05$; spatial frequency, $F(1, 2) = 53.727$, $P < 0.05$; luminance polarity, $F(1, 2) = 20.122$, $P < 0.05$). The result for the colour condition was not statistically significant ($F(1, 2) = 3.037$, $P > 0.05$).

The rate of spontaneous reversals was slightly higher in the non-segregated conditions, but the differences were not statistically significant (orientation, $F(1, 2) = 0.924$, $P > 0.05$; spatial frequency, $F(1, 2) = 7.344$, $P > 0.05$; luminance polarity, $F(1, 2) = 9.995$, $P > 0.05$; colour, $F(1, 2) = 0.228$, $P > 0.05$). The results with introduced rotation reversals are not therefore due to any differences in spontaneous reversal rates.

3. Experiment 2

In this experiment we consider the effects of feature swapping on the incidence of *illusory* rotation reversals, in order to decide whether featural information is incorporated before or after the formation of the cylinder's motion surfaces.

3.1. Methods

The methods in Experiment 2 were the same as those of Experiment 1, except that features were swapped instead of directions of rotation reversed. The task however was the same as in Experiment 1; subjects indicated each time they perceived the cylinder reverse its direction of rotation. Eight feature swaps were introduced during each stimulus presentation with the same constraints as employed in Experiment 1.

3.2. Results

The results are shown in Fig. 7. All three subjects perceived significantly more illusory rotation reversals when the surfaces of the cylinder were segregated by feature-type than when they were non-segregated (orientation, $F(1, 2) = 28.703$, $P < 0.05$; spatial frequency, $F(1, 2) = 37.416$, $P < 0.05$; luminance polarity $F(1, 2) = 23.572$, $P < 0.05$). For the colour condition, the difference between the two conditions was not statistically significant ($F(1, 2) = 1.315$, $P > 0.05$).

4. Discussion

In the first experiment, subjects perceived more physically-introduced rotation-direction reversals when the front/back surfaces of the cylinder were segregated by micropattern orientation, spatial frequency and luminance polarity, than when non-segregated. Segregation by colour did not significantly increase the number of perceived reversals. A control experiment showed that these results could not be accounted for on the basis of spontaneous reversals. The results with micropattern orientation confirm those from our previous study (Li & Kingdom, 1999). The results with micropattern spatial frequency and luminance polarity extend that study's finding to two other dimensions, demonstrating the generality of the phenomenon. There appears to exist a range of features to which 3-D SFM mechanisms are sensitive.

The lack of sensitivity to front/back differences in micropattern colour relates to two classes of previous experiments; those that use isoluminant stimuli, and those that use stimuli defined by both colour and luminance. Numerous studies attest to a weak, or non-existent, input of colour to motion processing at isoluminance (recently summarised by Yoshizawa, Mullen, & Baker, 2000). The weakness of perceived motion at isoluminance is especially compelling when the form of the stimulus is purely motion-defined (as here), such as with the red-green random-dot-kinematograms employed by Ramachandran and Gregory (1978). Their finding is paralleled by the compelling loss of stereo-depth observed in random-dot-stereograms at isoluminance (see recent review by Kingdom, Simmons, & Rainville, 1999). We have observed simulated rotating cylinders at isoluminance (see Section 3.1), and there is indeed an almost complete lack of any sensation of a rigid, rotating, 3-D object. Although these findings with isoluminant stimuli are consistent with the lack of a colour-segregation effect found in the present study, they do not necessarily imply a common cause. It is theoretically possible that 3-D SFM mechanisms are insensitive to colour contrast on its own, yet sensitive to *combinations* of colour and luminance contrast (i.e. bright red or dark green). The relevant experiments in this case are those that have investigated the role of colour in the perception of global motion, as these use micropatterns defined by both colour and luminance contrast (Croner & Albright, 1994; Edwards & Badcock, 1996; Li & Kingdom, 1998, 2001; Snowden & Edmunds, 1999). The task in these studies was to discriminate the direction of a set of coherently moving dots set amongst incoherently moving distractors, and the critical test was whether performance improved when the target and distractor dots (which all had luminance contrast), differed in colour. We have argued that the results of these studies are best understood by supposing that target-distractor colour difference only enhance performance when attention can be unambiguously directed towards the target elements (Li & Kingdom, 2001; see also Snowden & Edmunds, 1999, for a similar conclusion). A corollary to this conclusion is that in the global motion paradigm, motion mechanisms are *not* tuned for colour; put another way, the image is not automatically filtered into separate colour maps for motion processing. Although unlike in the global motion paradigm the experiments here did not involve selection of a 'target', the insensitivity to colour that we find is consistent with the results from studies of global motion.

Treue et al. (1995) and Hildreth, Ando, Andersen, and Treue (1995) have previously argued that physically-introduced reversals in simulated rotating cylinders are often missed because the surface interpolation mechanism that generates the percept of a rigid, 3-D, moving object does not preserve details of surface markings. However, our finding that the number of perceived reversals increased when the front/back surface micropatterns differed in a variety of feature-types suggests that while information about the *arrangement* of the micropatterns might be lost, details of the *types* of certain local feature are preserved.

Is featural information incorporated before or at the stage of 3-D object representation, the latter implying that 3-D SFM mechanisms are tuned, and motion surfaces labeled, for feature type? In our second experiment, when the features on the front/back surfaces of the cylinder were periodically swapped, subjects perceived more illusory reversals in the segregated compared to non-segregated conditions. We argue that this favours the mechanism tuning hypothesis in Fig. 8b. If the surfaces are labeled for feature-type (e.g. 'front surface is bright' and 'back surface is dark'), then swapping the features in the segregated condition would, according to the rigid body assumption, best be

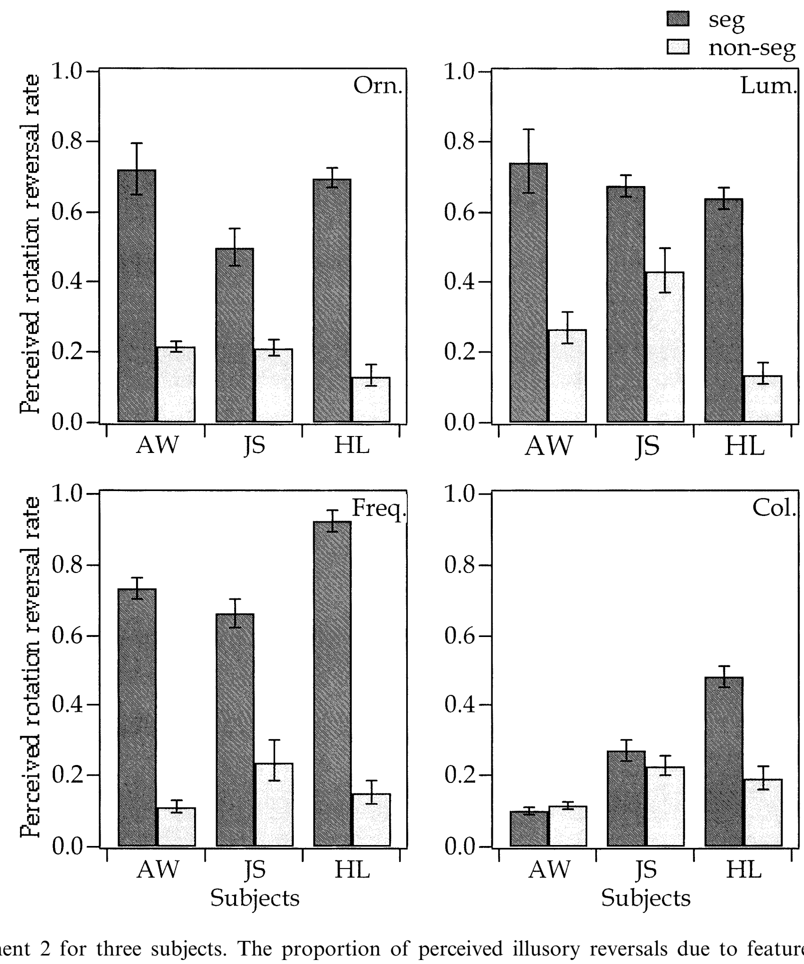

Fig. 7. Results for Experiment 2 for three subjects. The proportion of perceived illusory reversals due to feature-swapping is shown for both segregated and non-segregated conditions, and for four feature-types: (a) orientation (Orn.), (b) luminance polarity (Lum.), (c) spatial frequency (Freq.) and (d) colour (Col.). Error bars are standard errors.

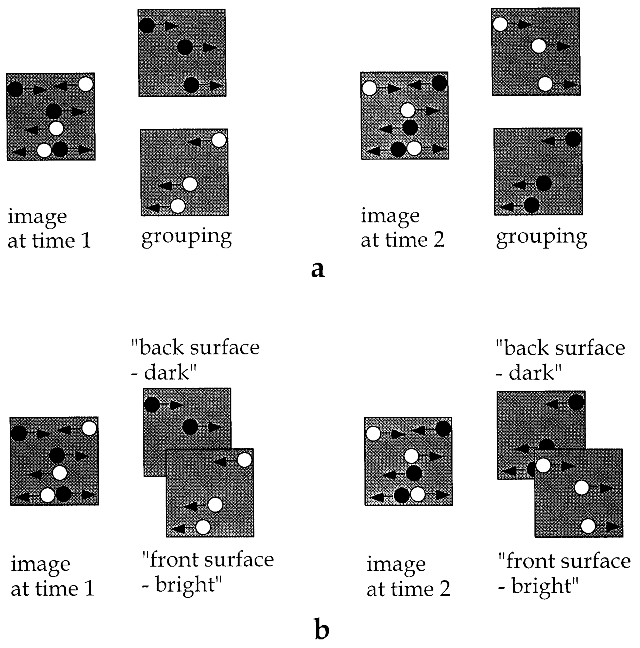

Fig. 8. Schematic representation of two hypotheses concerning the effects of 'feature-swapping': (a) grouping hypothesis; and (b) surface-labeling hypothesis. Each figure shows two motion frames of the cylinder whose front and back surfaces are made different luminance polarities of micropatterns, and the possible internal representations of such an arrangement. In both (a) and (b), the polarities swap from bright to dark and vice versa, with the rotation direction unchanged. (a) At time one, the micropatterns are grouped by luminance polarity prior to motion-surface processing. When the features swap from dark to bright and vice versa at time two, re-grouping may occur as at time one, but no perceived rotation reversals would be expected. (b) At time one, both surfaces are labeled by luminance polarity. The labeling persists even when the features are swapped, resulting in the perception of rotation reversals.

interpreted as a change in rotation direction rather than a change in the depth order of the surfaces (i.e. rotating bodies often change direction but do not turn themselves inside out!).

There have been a number of studies showing that additional depth information such as occlusion and disparity disambiguates the rotation direction of spheres simulated with parallel projection (Andersen & Braunstein, 1983; Braunstein et al., 1982; Braunstein, Andersen, Rouse, & Tittle, 1986), and Necker cubes (Dosher, Sperling, & Worst, 1986). For example, Dosher et al found that correlating the edge contrast of a Necker cube with distance (e.g. the distant edges had low contrast, the near edges high) disambiguated its perceived depth. It is unlikely however that depth disambiguation underlies the results with the segregated-by-feature-type stimuli; as none of the feature-types, with the exception of spatial frequency, are normally correlated with depth in the natural visual world.

Our results are also relevant to recent studies dealing with the phenomenon of motion inertia. In a series of experiments, Jiang et al. (1998) presented two short sequences of simulated 3-D spheres separated by an interval of variable duration (during which the dots were present but stationary) and recorded the perceived direction of rotation at the beginning of each sequence. They found that the perceived rotation direction of the first sequence influenced that of the second, arguing that this was an example of 3-D motion inertia. The effect was observed even when the two sequences were 800 ms apart. Jiang et al. suggested that the linkage between the direction of motion and the depth value of a dot (near or far) during the first sequence was preserved for the second sequence. In another experiment, Jiang et al. employed a feature-swapping technique similar to that used here, except the features were swapped *between* sequences, rather than *during* a sequence. They used two types of dots—high contrast and low contrast—and these were segregated onto the front and back surfaces of the sphere. Luminance contrast is known to provide depth-ordering information, i.e. high contrast dots generally appear to be nearer than low contrast ones, and Jiang et al. wanted to know whether this cue would override the visual inertia that they had demonstrated in their first experiment. For this purpose they swapped the contrasts of the dots at the onset of the second motion sequence. If the depth-ordering cue was dominant, the rotation direction would now be expected to reverse for the second sequence, but if inertia dominated, there would be no reversal. They found that swapping the contrast of the dots between sequences had little effect on perceived rotation direction, suggesting that 3-D visual inertia was the dominant influence.

In our experiment, we found that feature swapping *during* a sequence produced more illusory reversals in the feature-segregated compared to feature-non-segregated conditions. Does this contradict the findings of Jiang et al.? There are a number of differences between the stimuli in the two studies that could account for the difference in results. For example, we employed limited lifetime, as opposed to continuously moving dots, and our dot densities were higher than those used by Jiang et al. However, there are three differences in the stimuli that are particularly worth noting.

First, Jiang et al. used dots of the same polarity but different contrast, whereas we used dots of the same contrast but of opposite polarity. There is good evidence that opposite polarities of luminance contrast ('increments' and 'decrements') are processed by different mechanisms/pathways (Fiorentini, Baumgartner, Magnusson, Schiller, & Thomas, 1990), and this accords with our finding that 3-D SFM mechanisms appear to be selective for contrast polarity. A corollary to this conclusion is that 3-D SFM mechanisms may be unselective for contrast *magnitude*, and if so we would not expect that swapping contrast magnitudes would produce perceived rotation reversals, in keeping with the results of Jiang et al.

Second, our features were swapped during, rather than between sequences. As we argued above, feature swapping in our segregated condition is most parsimoniously interpreted by the visual system as a change in rotation direction rather than order of surface depth (because of the rigid body assumption), whereas swapping between sequences leaves the depth/direction relationships of the second sequence indeterminate, allowing visual inertia to exert its influence.

Third, our motion sequences, during which feature-swapping took place, were much longer than those employed by Jiang et al. Our motion sequences were of 13.3 s duration, during which there were eight feature swaps with a minimum between-swap time of 500 ms. The average between-swap time during which the cylinder rotated in apparent motion was therefore about 1.5 s. In Jiang et al.'s study the sphere rotated in apparent motion for only 200 ms in the first, and 300 ms during the second sequence. If 3-D SFM mechanisms have relatively poor temporal resolution, then sensitivity to the feature content of the motion surfaces they generate may only manifest itself with motion sequences longer than those used by Jiang et al. Some recent experiments by Pantle, Papp, Reynolds, Cubells and Gallogly (1998) are relevant here. Using simulated 3-D spheres they determined that 3-D motion inertia was based on a viewer-centred (tied to retinal direction of motion and dependent upon a viewer's orientation) rather than world-centered (independent of the orientation of the viewer) coordinate system. Furthermore, they showed that 3-D motion inertia was only operative when the depth of the simulated 3-D spheres had apparently collapsed. Pantle et al. argued that 3-D motion inertia exerted its influence *early* in the formation of the 3-D motion percept, and operated at the level of each dot. Our finding that feature-swapping in the segregated condition overcame 3-D inertia and produced apparent rotation reversal thus likely reflects the influence of higher-level *surface* labeling processes.

5. Conclusion

3-D SFM mechanisms are sensitive to the orientation, spatial frequency, luminance-contrast polarity, but not colour contrast of surface markings, even though insensitive to the particular arrangement of those features. The sensitivity appears to reflect feature-specific tuning of 3-D SFM mechanisms.

Acknowledgements

This research was supported by Medical Research Council of Canada grant (Grant MT 11554) awarded to Frederick Kingdom.

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