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Illusory depth from moving subjective figures and neon colour spreading

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Abstract. If a pattern of concentric circles, interrupted so as to produce the perception of a subjective bar extending from the centre to the periphery of the pattern, was slowly rotated in a plane perpendicular to the line of sight, observers reported seeing the bar slanted in depth and moving over complete and stationary concentric circles. When the interrupted concentric circles were completed by red segments—thereby giving rise to a neon colour-spreading effect— observers reported seeing a reddish bar, which sometimes appeared to be slanted in depth, moving behind the plane of the concentric circles. A combination of the two patterns was found to originate a compelling percept of a unitary bar slanted in depth: part of the bar (the subjective half) appeared to be located in front of its inducing elements, whereas the other part (the neon-like half) appeared to continue behind them. When translatory instead of rotary motion was used, the bars did not look slanted in depth: however, the neon bar appeared either behind or in front of the inducing lines, depending on the luminance contrast between the segments and the inducing lines themselves.

1 Introduction

Stereokinetic effects occur when two-dimensional patterns are seen to deform or to become three-dimensional as they are rotated in a plane perpendicular to the line of sight (see Musatti 1924; Braunstein 1976; Wilson et al 1983; Bressan and Vallortigara 1986a, 1987; Vallortigara et al 1986; Zanforlin 1988; Zanforlin and Vallortigara 1988).

We (Bressan and Vallortigara 1986b) have recently reported that subjective contours can produce stereokinetic effects. By using an illusory contour ellipse formed from interruptions in a pattern of concentric circles, we found that rotation of the pattern in the frontoparallel plane was able to induce the impression of a subjective circular ring tilting back and forth over the plane of the circles. In this paper we extend these observations and show that, under certain circumstances, neon colour-spreading patterns also allow vivid perceptions of illusory depth when rotated in the frontoparallel plane. We also found that a different type of depth effect can be obtained by using translatory instead of rotary motion.

2 **Rotation of illusory and neon-spreading patterns**

2.1 *Experiment 1*

2.1.1 *Method.* Each of the five patterns depicted in figures 1 and 2 was rotated on a turntable at a speed of 8 rev min^{-1} in the frontoparallel plane under normal lighting conditions. Eight naive subjects served as observers. They were individually seated in front of the turntable at a distance of 100 cm (patterns subtended a visual angle of about 8 deg) and were asked to report what they saw. Patterns were presented in a randomized order to minimize the likelihood of a response bias.

2.1.2 *Results and discussion.* Consider the pattern shown in figure la. When this figure was rotated, all subjects reported seeing the illusory bar slanted in depth, with its central end pivoting on the plane of the circles and its peripheral end located closer to the observer. The concentric circles appeared to be stationary and complete, though periodically occluded by the anomalous line during its movement. The perceived slant of the line with respect to the frontoparallel plane was about 40°-50° on average.

When the gaps in the concentric circles were replaced by red arcs (see figure 1b), thereby originating a neon colour-spreading effect (Van Tuijl 1975), subjects reported seeing a reddish bar moving behind the circles. For half of the subjects the bar appeared to be perpendicular to the line of sight (parallel to the plane of the circles) and retained this orientation during its movement. For the other half, on the contrary, it appeared to lie obliquely, in which case the peripheral end was the farthest away from the plane of the concentric circles, while the central end appeared to be anchored to the plane itself. This particular depth effect was at any rate much less stable than that obtained with the pattern reproduced in figure 1 a. By using a combination of the two patterns, however, (shown in figure 2a) the effect became absolutely compelling. Subjects reported that the entire bar was slanted in depth: one half (that bounded by subjective contours) appeared over the plane of the circles, whereas the other half (that produced by neon spreading) continued behind the plane of the circles and had a different colour (reddish).

Note that a similar result was not achieved when using a pattern like that shown in figure 2b. In this case dislocation in depth of the bar was probably prevented by the absence of occlusion information over the half of the bar that would be expected to lie behind the circles. Thus, the prevalent impression was that of an anomalous bar sliding on top of a plane of motionless concentric circles. Conversely, the pattern depicted in figure 2c gave rise to a perceptual outcome very similar in all respects to that produced by the pattern in figure 2b, except that the long reddish bar now appeared to slide behind the concentric circles.

We think that at least three aspects of these illusions deserve a special mention:

(i) Even those subjects who did not see the reddish bar slanted in depth in figure lb reported a compelling depth impression when presented with the pattern shown in figure 2a. In principle, there is no reason why the pattern shown in figure 2a could not have produced, at least for these subjects, a simple addition of the two effects, ie half of the bar (subjective) tilted in depth, and the other half (neon-like) lying in a plane perpendicular to the line of sight. This solution might also have been favoured by the fact that the two halves of the bar were of different colours. However, this percept was never reported. We think that this is a good demonstration of the Gestalt law of ‘good continuation’.

(ii) The neon-like patterns always appeared to be located behind the concentric circles. As far as we know, this is the first report of a subjective figure which lies behind its inducing elements.

(iii) When these moving neon-like patterns are observed preattentively (ie without scrutinizing the individual red segments), the impression is that only the bar has a distinct neon-likes hue, whereas the concentric circles appear to be uniformly black. (This effect is particularly strong for the pattern shown in figure 2a.) Since a similar effect does not occur if the pattern is stationary, it seems that depth through motion can affect the way in which the visual system shares out colours between different object surfaces.

3 Luminance and depth stratification

The results reported above seem to indicate that there are two different and perhaps dissociable depth effects: one affects the location of the illusory bar with respect to the plane of the inducing elements, and the other affects the slant of the illusory bar, regardless of its location. The first refers to the fact that the bar is resting on the frontal plane and moves either in front of or behind the plane of the inducers. The second refers to the fact that the bar appears to be slanted in depth, either in front of, behind, or through the plane of the inducers. The slant of the bar seems to be associated with the stereokinetic transformation. The stratification in depth, on the other hand, does not depend on the attainment of the stereokinetic effect and appears instead to be connected with the presence or absence of the coloured arcs of the circles. This suggests that the luminance relationships between the arcs of the circles and either the inducing lines or the background might play a critical role in the process of depth stratification. The following formal experiment was carried out with the aim of checking this conjecture.

3.1 *Experiment 2: rotation*

3.1.1 *Method.* Stimuli were created with an Apple Macintosh IIx computer and were displayed on its 13-inch high-resolution colour screen. Patterns were similar to those shown in figure 2c (full-length neon bar) and in figure 2a (half subjective half neon bar). To make the experiment as precise as possible, we chose to use grey rather than coloured segments. Neon bars were thus the result of neon brightness spreading (rather than neon colour spreading). The grey segments were 3 mm long and created a bar that measured 78 mm from end to end. The diameter of the largest circle was 120 mm and the whole pattern rotated at a speed of 14 rev min^{-1}. The viewing distance was 100 cm.

The experiment was divided into two parts. In the first part, six stimuli like those shown in figure 2c were used. Three of the stimuli had black (0.452 cd m^{-2}) inducing lines and were presented on a white (43.168 cd m^{-2}) background; the other three had white inducing lines and were presented on a black background. For each background condition the three stimuli were identical, except for the luminance of the grey segments which was either 7.708, 17.884, or 30.183 cd m^{-2}.

For each background condition the three stimuli were presented four times each, giving a total of twenty-four presentations; the order of conditions and of stimuli within conditions was randomized. The second part of the experiment was in all respects identical to the first, except for the type of stimulus (half subjective half neon bars, rather than full-length neon bars). Two naive subjects and one of the two authors (GV) took part in the experiment.

3.1.2 *Results and discussion.* Results for the full-length neon bar are shown in figure 3. As can be seen the neon bar appeared to be in front of the inducers when the luminance difference between the segments and the inducing lines was high, but appeared to be behind when the difference was low. In the latter case, as a matter of fact, the neon bar tended to be seen as behind the lines even in static conditions, particularly in peripheral vision.

The results seem to indicate that, when the luminance difference between segments and inducing lines is low, the brightness changes within the lines can be disregarded by the visual system; the resulting organization is that of a pattern of uniformly black lines partially occluding a grey elongated shadow sliding on the background. When the luminance difference is large, on the other hand, the uniformity of the lines can be maintained only if the variation in brightness is attributed to a transparent veil moving in front of the lines.

It is worth noting that no stereokinetic effects were reported when using full-length neon patterns. When we used patterns like that depicted in figure 2a, however, all subjects reported the impression of a single straight bar crossing the plane of the circles slantwise. Within the whole range of luminances that we used, the subjective half of the segment invariably appeared in front of the inducing circles and the neon half invariably behind the circles.

It seems, therefore, that the occurrence of stereokinesis is severely limited by occlusion information (the full-length subjective bar and the neon bar never undergo stereokinetic transformation), but is relatively insensitive to brightness information affecting depth stratification (in our case, to the location of the neon bar with respect to the plane of the inducers). Since the middle of the bar (the point with zero velocity) acts as an anchor point located in the same depth plane as the inducers, full-length subjective bars (figure 2b) or neon bars (figure 2c) cannot be slanted in depth because of clashing occlusion information in the area that should shift behind (with subjective patterns) or in front of (with neon patterns) the inducers. Yet, using the pattern of figure 2a, in which occlusion information is compatible with the slanting in depth of the bar, the effect was perceived regardless of the luminance relationships around the neon-like area of the bar. Clearly, the tendency towards this particular depth organization is strong enough to win under even the most unfavourable brightness conditions.

3.2 *Experiment 3: translation*

Since the inducing concentric circles used in experiments 1 and 2 are optically stationary, and the effect of luminance contrast on depth stratification is not dependent on the stereokinetic transformation, one may infer that results similar to those described above should also be found when using translatory rather than rotary motion. An additional experiment was performed to address this point.

3.2.1 *Method.* Stimulus configurations were created with the apparatus described for experiment 2. The stimuli were full-length neon bars in the first part of the experiment, and half subjective half neon bars in the second part. In each trial, the bar moved horizontally, at a speed of 3.56 cm s^{-1} across a field of horizontal inducing lines. The configuration was 12 cm high and 18 cm wide. Line thicknesses, segment lengths, luminance levels, and viewing conditions were the same as in experiment 2. Two naive subjects and one of the authors (GV) took part in the experiment.

3.2.2 *Results and discussion.* The results for full-length neon bars are shown in figure 4. As can be seen the general outcome was identical to that observed with rotary motion: the neon bar appeared either behind or in front of the inducers, depending on the luminance difference between segments and inducing lines.

Using patterns composed of half subjective and half neon bars, however, the results were strikingly different from those observed with rotary motion (see figure 5). Whereas the subjective half always appeared to be in front of the inducers, the neon half appeared to be either in front of or behind the inducers depending, again, on the luminance difference between the segments and the lines. Interestingly, the subjects never reported that the bar appeared to be slanting when its neon half seemed to be located behind the inducing lines; instead the prevailing percept was that of two independent segments lying on the frontal plane at different distances. It is fair to conclude that, in absence of stereokinesis, the stratification in depth of the neon bar depends entirely on the luminance relationships between the segments and the inducing lines.

4 General discussion

The effects obtained using translatory motion may be accounted for on the basis of the mechanisms of kinetic occlusion and of visual transparency. The most intriguing aspects of these effects seem to be related to the relative insensitivity of the visual system to weak luminance variations between segments and inducing lines. When, however, luminance differences are too strong, a superimposed translucent veil must be postulated to account for the discontinuities perceived within the lines. Note that when the contrast between the segments and the lines is decreased by lowering their luminance difference, the contrast between the neon veil and the background is presumably decreased as well. In both cases the residual brightness differences are very small; they occur, however, between regions of different spatial extent. One could argue that, if neglect of brightness differences does occur, it might occur more readily in the thin inducing lines than around the longer boundaries between the neon surface and the surround. In this case, occlusion (the lines perceived as uniform) rather than transparency (the lines not perceived as uniform) would naturally follow.

Alternatively, it could be claimed that when luminance differences between the segments and the inducing lines are very small, the subjective surface will be less vivid (Frisby and Clatworthy 1975), and it may be that the perception of transparency is impaired when the transparent surface has no clear-cut contours. Another speculation is suggested by Watanabe and Sato's (1989) recent demonstration that under conditions of isoluminance, chromatic neon spreading is present but reduced in extent to about half of what it is when bounded by subjective contours. Therefore the probability of perceiving a translucent veil may be reduced if the brightness gap in the inducers does not coincide with the spatial extent of the neon area.

The special depth effect produced under stereokinetic conditions, however, deserves further research. Unlike the one described above, this effect is only obtained through rotary motion; it is very strong and is relatively unaffected by the amount of brightness difference present within the lines. In fact, the effect observed with the pattern shown in figure 2a was reported for all the combinations of luminances we used.

The phenomena described in this paper seem to provide evidence for a close relationship between subjective contours, neon spreading, transparency, and depth. This is, we think, of theoretical importance. Physiological research points out that colour, subjective figures, and depth have separate representations in extrastriate cortical areas (Zeki 1978; van Essen and Maunsell 1983; von der Heydt et al 1984). More generally, the idea has been stressed that different functional streams are responsible for the encoding of distinct aspects of an image, and that these cortical representations show considerable segregation (Hubel and Livingstone 1987; Livingstone and Hubel 1987). However, our results indicate that, at some level, depth signals can affect chromatic signals by changing, for instance, the semitransparent colour of a two-dimensional rectangle into the volume colour of a three-dimensional rod (see figure 2a). All this hints at interaction rather than segregation. Notice that similar connections between subjective figures, neon spreading, transparency, and depth have been demonstrated by Meyer and Dougherty (1987) and by Nakayama et al (1989) through manipulation of flicker-induced depth and stereoscopic depth, respectively. This suggests that the effect of depth signals on chromatic processing is rather general and independent of how the depth signals themselves are generated.

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