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Flank transparency: The effects of gaps, line spacing, and apparent motion

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Abstract. We analyze the properties of a dynamic color-spreading display created by adding narrow colored flanks to rigidly moving black lines where these lines fall in the interior of a stationary virtual disk. This recently introduced display (Wollschläger et al, 2001 *Perception* **30** 1423 – 1426) induces the perception of a colored transparent disk bounded by strong illusory contours. It provides a link between the classical neon-color-spreading effect and edge-induced color spreading as discussed by Pinna et al (2001 *Vision Research* **41** 2669 – 2676). We performed three experiments to quantitatively study (i) the enhancing influence of apparent motion; (ii) the degrading effect of small spatial discontinuities (gaps) between lines and flanks; and (iii) the spatial extent of the color spreading. We interpret the results as due to varying degrees of objecthood of the dynamically specified disk: increased objecthood leads to increased surface visibility in both contour and color.

1 Introduction

Neon color spreading refers to the perceptual phenomenon of color that seems to disperse from image elements into their surround, thereby creating a subtle neon-like veil. The observed coloration overcomes 'real' figure boundaries and typically covers an area confined by subjective contours (Schumann 1900; Takeichi et al 1992). Neon-color-spreading displays usually share a common construction principle: differently colored segments are embedded in a line drawing to form a virtual contour. While the phenomenon of color spreading was probably known and systematically exploited for practical use as early as in the 16th and 17th century, the first scientific accounts were given by Wallach (1935), Varin (1971), and van Tuijl (1975).

Other classes of stimuli which differ in their construction from displays originally employed have been shown to elicit some form of color spreading, as well. Color-from-motion displays created by Cicerone and Hoffman (1992; Cicerone et al 1995) and Shipley and Kellman (1993, 1994) use apparent motion to induce the perception of subjective contours filled with color diffused from stimulus elements lying in the interior of a motion-determined virtual disk. In this display, the strength of the color-spreading effect was shown to be modulated by the amount of perceived motion in the display. In particular, apparent motion was shown to considerably enhance the color-spreading effect.

A class of static stimuli devised by Redies and Spillmann (1981; Redies et al 1984) demonstrates that in some cases color disperses only in the vicinity of colored figure elements, yielding the perception of narrow tinted flanks alongside them. The authors propose that this 'neon-flanks' phenomenon can be taken as a basic local effect which in accumulation serves to create global neon spreading as a lateral extension (see also Watanabe and Takeichi 1990). On the basis of their findings on fringe-induced color spreading in the modified McCollough effect (McCollough 1965), Broerse et al (1999),

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however, argue that different mechanisms are responsible for the narrow color spreading confined to edges (‘edge colors’) on the one hand, and global color spreading (‘spread colors’) on the other hand.

Pinna et al (2001) report that, in their similarly constructed ‘watercolor-effect’ displays (figure 1a), the flank-induced coloration has no neon-like quality and much more resembles pastel surface colors. They also show that the area covered by the ‘diffused watercolor’ can be much larger than what is usually bridged by neon color spreading.

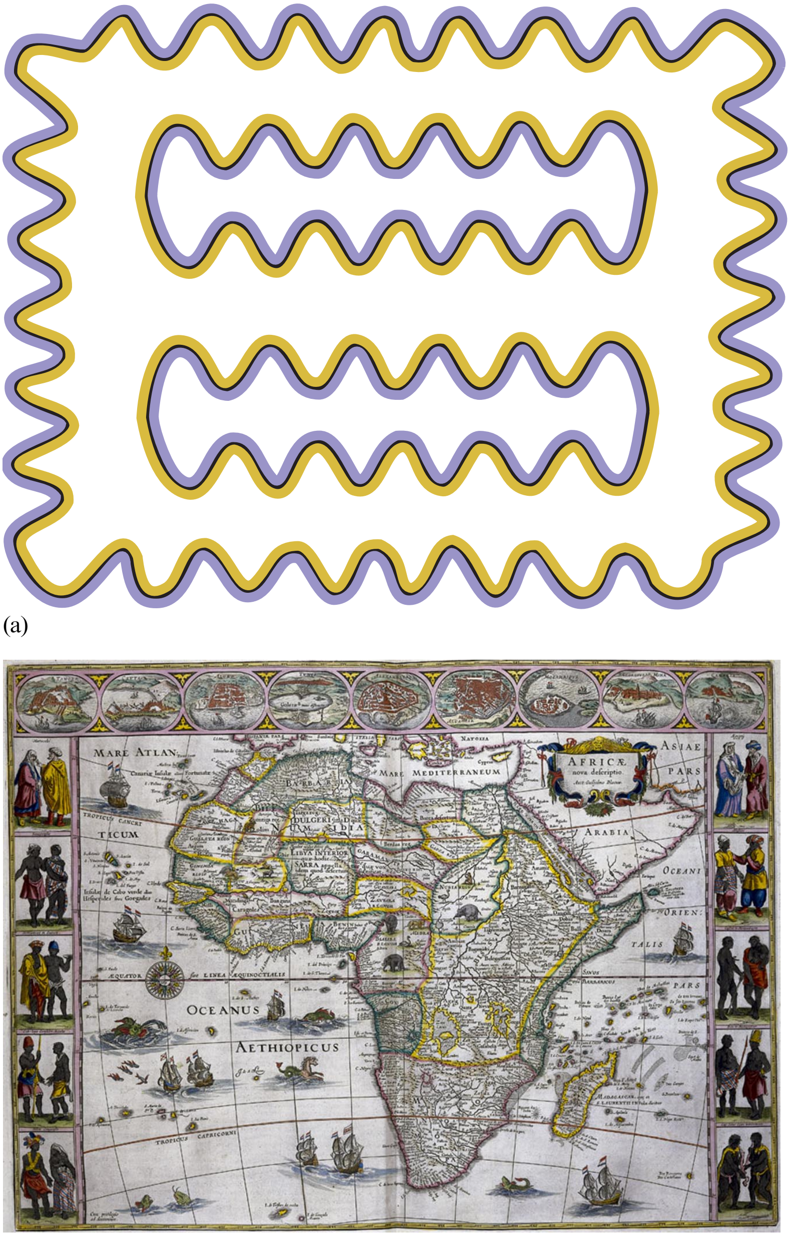


Figure 1. (a) Watercolor-illusion display, adapted from Pinna et al 2001. (b) Map drawn by Johan Blaeu (1663) by the outline-color technique. [By permission of The British Library: Maps.C.5.b.1.] Figures 1 and 2 are shown in color on the web.

Pinna et al further stress that in their case no transparency is observed, a characteristic that is shared by most classical neon-color-spreading displays.

Typically, the region encompassed by neon color spreading appears—albeit sometimes faintly so—as a transparent layer (Bressan et al 1997; Ekroll and Faul 2002; Nakayama et al 1990; Varin 1971). While transparency serves as a defining attribute of neon color spreading, its intrinsic relationship to the spreading component remains a debated issue. In the flank-induced transparency illusion described below (henceforth called 'flank transparency' for short), observers consistently report that perceptual transparency coincides with color spreading.

Pinna et al (2001) suggest that the watercolor effect can influence the perception of figure and ground. Taken together with the considerable spatial extent of the color spreading, this offers some insight into coloring techniques used by Renaissance map makers during the late 16th and the 17th century. In some maps from this epoch, regions are painted in outlines only, with flanking colored lines alongside them (figure 1b). This 'outline-color technique' is prominently featured, eg in Johan Blaeu's maps (Bagrow and Skelton 1985; Shirley 1983). The result is a layout that looks strikingly similar to the watercolor effect (figure 1a). Map makers evidently employed color-spreading effects in a systematic way to ensure that countries are easily silhouetted against each other without having to be drawn in solid colors. Although the induced color spreading must overcome frequent 'barriers' in the form of location names—and is therefore somewhat weak—the effectiveness of the technique is evident in original maps made this way.(1)

2 Flank transparency

Flank transparency arises from combining dynamic color spreading (see, eg, Cicerone et al 1995) with Pinna's watercolor effect (Pinna et al 2001). The display contains a virtual disk that appears to move relative to an array of solid line segments spread on a uniformly colored background. The line segments are arranged such that their center points form a square grid, and their orientations are pseudorandom. All line segments have the same color that is different from the uniformly colored background. A stationary virtual disk is then defined which is horizontally and vertically centered on the screen. The line segments are rigidly translated a slight amount in a horizontal direction in each frame, and narrow colored flanks are added parallel to these segments where they lie in the interior of the virtual disk (figures 2a and 2b). While a single frame alone produces a relatively weak impression of illusory contours and color spreading, the animated display yields compelling color spreading and the clear perception of a moving transparent filter with well-defined boundaries.(2)

We found that the color-spreading effect evoked by a flank-transparency display is sufficiently strong to warrant quantitative color-matching tasks. This is in contrast to many static neon-spreading stimuli, which often have a slightly elusive quality and are perceptually unstable.

In the experiments performed here, the display was horizontally split into two parts. While the top half contained the stimulus described above—the virtual disk now being a half-disk—the bottom half was used for displaying either a complementary solid half-disk for a color-matching procedure, or a number for a magnitude-estimation task. The background of the bottom half was uniform and of the same color as the background in the top half (figures 2c and 2d).

In preliminary studies, we had found this display equivalent to one with a static background and a moving virtual disk, the setup chosen by Cicerone et al (1995).

(1) Pinna et al (2001) indeed hint at a possible application in map making, but they do not elaborate further on this thought.

(2) A version of this display can be found at http://aris.ss.uci.edu/cogsci/personnel/hoffman/Applets/Outline/Outline.html

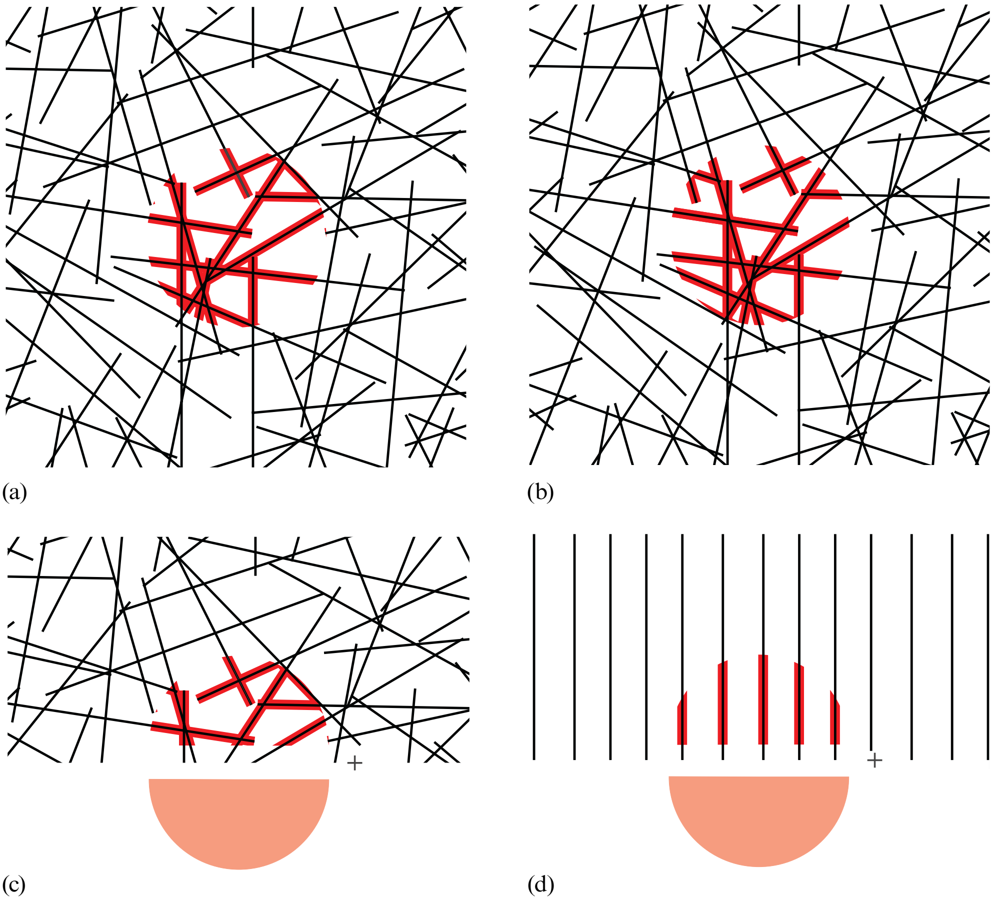


Figure 2. (a) and (b) Two frames from a flank-transparency display. The random line array is slightly shifted to the right between frames, whereas the illusory circle stays put. (c) Flank-transparency display as used in experiment 1. The bottom half displays a half-disk used for a color-matching procedure. (d) Experimental display as used in experiment 3.

However, keeping the disk stationary has several advantages: the display allows for a fixed eye position, thus avoiding potential blurring effects of smooth-pursuit eye movements. Color-matching tasks seem to benefit from a stationary disk, as we had found the comparison between static objects easier to perform than between moving objects. Furthermore, with an illusory half-disk in the top half of the display and a complementary solid half-disk in the bottom half, the display adheres more closely to conventional color-matching setups.

3 Experiments

Three experiments were performed in order to examine (i) the effect of apparent motion, (ii) the result of introducing small spatial discontinuities (gaps) between lines and flanks, and (iii) the spatial extent of the color spreading.

In experiment 1, we studied the influence of apparent motion on brightness and saturation of the virtual disk, as well as on perceived strength of its boundaries. We observed that increased apparent motion resulted in stronger subjective boundaries and a darker, more saturated illusory disk. Results are compared to those by Cicerone et al (1995), obtained in a similar task. In experiment 2, we explored the relationship between the gap size between lines and flanks and observers' color matches and boundary-strength ratings. We showed that with the introduction of gaps, boundary strength decreases, and the illusory disk appears lighter and desaturated. Results are related to findings in comparable experiments about color spreading in the Ehrenstein figure (Redies and Spillmann 1981) and to characteristic attributes of the watercolor effect (Pinna et al 2001). In experiment 3 we estimated the spatial extent over which color spreading can operate in our display. We obtained a measure for spatial drop-off and compared it to that of other neon-spreading displays. Results indicate that the color spreading in dynamic flank-transparency displays extends over distances much smaller than those described by Pinna et al (2001) for the watercolor effect.

3.1 *Experiment 1: Velocity of moving lines*

3.1.1 *Participants.* Five observers with normal color vision and normal or corrected-to-normal visual acuity participated in the experiment, including two of the authors (TR, DW). The remaining subjects were naïve to the purpose of the experiment.

3.1.2 *Stimuli.* The background of the display was white with CIE 1931 (Wyszecki and Stiles 1982) coordinates $x = 0.29$, $y = 0.31$, $L = 70$ cd m^{-2}, and comprised a visual angle of 18 deg by 11 deg. The display was bipartite, the upper half contained the dynamic color-spreading stimulus, the lower half the figures used for a match and a rating task described below.

The dynamic stimulus contained randomly oriented black lines (CIE $x = 0.29$, $y = 0.31$, $L < 0.2$ cd m^{-2}) of width 13.6 min of arc and length 2.27 deg. Red (CIE $x = 0.48$, $y = 0.33$, $L = 14$ cd m^{-2}), and in a separate session green (CIE $x = 0.29$, $y = 0.45$, $L = 14$ cd m^{-2}) flanks of 2.73 min of arc width were added parallel to the lines on both of their sides in the interior of a virtual half-disk with a radius of 1.6 deg. A fixation cross was placed on the horizontal center line at an eccentricity of 9.55 min of arc to the disk boundary, because our studies had indicated that color spreading was strongest under parafoveal viewing conditions.

In the first task, a solid complementary half-disk for doing a color match was displayed in the lower half of the screen on the same white background as the upper half. The two half-disks were separated from each other by 1 deg in order to avoid perceptual interactions between the illusory disk and the real disk. Otherwise, the real half-disk would adversely affect color spreading in the motion-defined disk when placed immediately adjacent to it. In the second task, the lower half displayed a number from 1 to 10, corresponding to an observer's rating entered on the keyboard.

The line array rigidly moved to the right in unison, whereas the virtual half-disk remained stationary at the center of the screen. The trailing side of the display was continuously replenished with lines. The velocity of the moving lines was modified purely through timed delays between changes of their position, translating into speed of apparent motion. The length of the discrete 'jumps' of the lines from one frame to the next, as well as the physical refresh rate of the monitor, was constant over different speeds.

3.1.3 *Design.* The independent variable was apparent velocity of the moving line array. A flank-transparency display was presented at one of three different speeds, either 0.5, 1.5, or 2.5 deg s^{-1}. Subjects performed 10 repetitions for each of the three speeds in pseudorandom order. The experiment was conducted twice, once for red and once for green flanks.

3.1.4 *Apparatus.* The stimuli were displayed on an Apple Studio 17 inch color monitor with the use of the OpenGL library. Color resolution for each pixel was 8 bits for each channel R, G, and B. Following a procedure described by Brainard (1989), we calibrated and gamma-corrected the monitor using a Spectracolorimeter (Photo Research, PR-650). Observers viewed the display in a darkened room at a distance of 80 cm.

3.1.5 *Procedure.* The observer's task in a given trial was twofold. First, the observer matched the color of the virtual disk in the upper half of the screen by adjusting the color of a solid half-disk in the lower half using the arrow keys on the computer keyboard. Pilot studies had indicated that perceived hue of the illusory disk was not affected by the experimental manipulations, so we restricted the subjects' settings to a plane of constant dominant wavelength, corresponding perceptually to a constant hue. Subjects thus controlled luminance and saturation. The hue was fixed to be identical to that of the flanks. This restriction helped reduce the complexity of the color-matching procedure and increase reliability. Before each new trial, the luminance and saturation of this half-disk were preset to a random value in the chosen plane of constant hue. Prior to the experiments, all subjects completed as many training trials as were needed to become sufficiently familiar with the task of adjusting a color in the chosen two-dimensional plane in color space.

In the second task, subjects were asked to give a rating of perceived boundary strength of the illusory disk on a scale ranging from 0 to 10, using the arrow keys on the keyboard to increase or decrease the displayed number on the screen. The endpoints of the scale were anchored verbally, with 0 corresponding to no perception of illusory contours, and 10 corresponding to most highly apparent illusory contours. Examples of different illusory boundary strengths were provided to illustrate the possible range of the scale, with examples of apparent illusory contours such as Kanizsa's (1955) triangle and Albert and Hoffman's (1995) magic square.

Subjects were instructed to maintain fixation on the cross to reduce possible blurring effects of eye movements. There was no time limit for either task—subjects pressed a key to confirm their settings, and continued with the next trial.

3.1.6 *Results.* Figure 3 shows the results for the subjects' ratings in the first experiment for red and green flanks. Ratings for perceived boundary strength increased monotonically for each subject with increasing speed of the line array. The effect of apparent motion on the observers' ratings was significant in an ANOVA performed on the across-subjects data for red ($F_{2,147} = 254.2$, $p < 0.001$) as well as for green ($F_{2,147} = 164.9$, $p < 0.001$) flanks. Significant a posteriori Scheffé tests ($p < 0.001$) indicated that average ratings decreased from each speed to the next slower one.

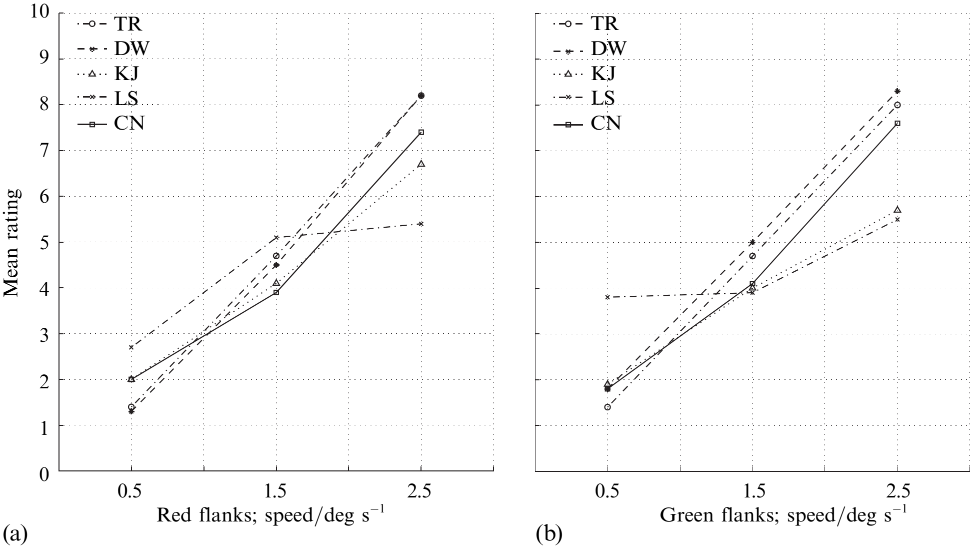


Figure 3. Mean boundary-strength ratings in experiment 1 for slow, medium, and fast speed (a) for red flanks and (b) for green flanks.

Figure 4 presents data obtained from the color-matching task in experiment 1. It shows the settings for red flanks for two of the five observers in an excitation purity (Wyszecki and Stiles 1982) by luminance color space. The axes correspond to the two dimensions available to the subjects for the color matches. Results indicate that with increasing speed the illusory disk appeared darker and more saturated than at slower speeds. This pattern was observed in four of the five subjects (table 1), with considerable inter-subject variability in the absolute location of the matches. One subject's (KJ) settings did not substantially differ between conditions. Except for this subject, the centroids for each subject's matches in the three conditions are approximately equally spaced, ie no two conditions group together.

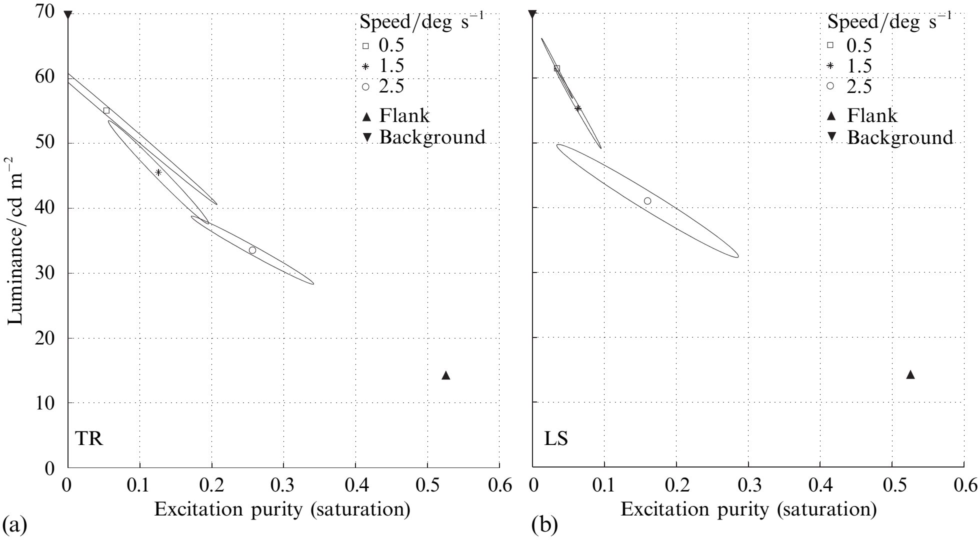


Figure 4. Color matches and corresponding 95% confidence ellipses in experiment 1 for red flanks. (a) Observer TR. (b) Observer LS. See table 1 for data from the other subjects.

With green flanks, data were generally less systematic than with red flanks. Increasing saturation resulting from higher velocities was observed for three (TR, KJ, CN) of the five subjects, decreasing luminance for two subjects (TR, CN) (table 1). The remainder of the observers did not exhibit a systematic pattern of change between conditions.

3.1.7 *Discussion.* Experiment 1 provides good support for the conclusion of Cicerone et al (1995) that "color spreading is yoked to the perception of apparent motion" (page 763). Although constructed in a different way, our display behaves like color-from-motion stimuli employed by Cicerone et al, who also found that ratings for boundary strength are higher for faster-moving stimuli. In addition, we quantified the effects of increasing speed on subjects' settings in a color-matching task. Color spreading increased with higher velocities in the sense that the illusory disk acquired a darker and more saturated color.

Speaking in terms of transparency, the reduction in color spreading at slower speeds corresponds to the impression of a filter that becomes more and more translucent and less visible itself. The fact that with decreasing speed the color matches approach the color and luminance of the background has an interpretation within additive transparency models, for instance the episcotister model (D'Zmura et al 1997; Gerbino 1994; Metelli 1974). It means that more and more light reflected from the white background is mixed with proportionally less light reflected from the filter.

The increase in color spreading with increasing speed is paralleled by an increase in ratings for perceived boundary strength of the illusory disk, indicating that the perceived

Table 1. Mean color matches (CIE *x*, *y*, $L/\mathrm{cd\ m}^{-2}$) in experiment 1 for red and green flanks.

Subject	Parameter	Red flank, speed/deg s^{-1}			Green flank, speed/deg s^{-1}		
		0.5	1.5	2.5	0.5	1.5	2.5
TR	x	0.31	0.34	0.38	0.29	0.29	0.29
	y	0.31	0.32	0.32	0.33	0.35	0.38
	$L/\mathrm{cd\ m}^{-2}$	55.1	45.6	33.5	65.3	63.3	59.8
DW	x	0.46	0.48	0.50	0.29	0.29	0.29
	y	0.33	0.33	0.33	0.53	0.55	0.55
	$L/\mathrm{cd\ m}^{-2}$	23.8	22.1	21.0	12.5	11.1	13.9
KJ	x	0.52	0.52	0.52	0.29	0.29	0.29
	y	0.33	0.33	0.33	0.48	0.48	0.50
	$L/\mathrm{cd\ m}^{-2}$	18.1	18.9	18.3	8.9	9.6	9.4
LS	x	0.30	0.31	0.35	0.29	0.29	0.29
	y	0.31	0.31	0.32	0.34	0.33	0.34
	$L/\mathrm{cd\ m}^{-2}$	61.5	55.3	41.0	65.0	65.2	64.8
CN	x	0.30	0.30	0.32	0.29	0.29	0.29
	y	0.31	0.31	0.31	0.32	0.32	0.33
	$L/\mathrm{cd\ m}^{-2}$	63.3	60.8	53.7	65.6	63.2	58.7

layer became more visible as a whole through better specification of its contours and its surface color.

However, the patterns of increasing saturation and decreasing luminance with higher speeds was not evident in the data of all subjects. We will consider two reasons for this inter-subject variability.

First, one subject's (KJ) matches were all very close to the monitor gamut, possibly indicating that only unsatisfactory matches were possible because of monitor restrictions. Second, one might argue that the nature of the matching task is fairly abstract owing to the different phenomenological qualities of the regions that are to be matched: whereas the illusory disk appears transparent, the adjusted reference patch appears as a matte opaque surface color. As a result, the two regions never look truly identical. Thus, the subjects' task effectively was to maximize the similarity between target and matching region. It required a concentration on particular aspects of the display, like saturation and lightness, while other aspects like opacity had to be discounted. This apparently led to a reduced accuracy of the matchings and to greater dissimilarities between data of different subjects. Nevertheless, as we have just seen, our data can be readily interpreted.

3.2 *Experiment 2: Modulating gap size*

3.2.1 *Participants.* The same five subjects from experiment 1 participated in experiment 2.

3.2.2 *Stimuli.* The stimuli were the same as in experiment 1 with the difference that gaps of varying size were introduced between the colored flanks and the line segments. Over time, this manipulation did not affect the summed length of flanks in the motion-defined disk, but merely changed the spatial location of the flanks. The speed of the moving line segments was kept constant at 2.5 deg s^{-1}, the speed we had found optimal in experiment 1 for creating a strong color-spreading effect. In this and the following experiment, only red (CIE $x = 0.48$, $y = 0.33$, $L = 14\ \mathrm{cd\ m}^{-2}$) flanks were used.

3.2.3 *Design.* The independent variable was size of the gap between the colored flanks and the line segments. The three gap sizes employed were no gap, 1.36, and 2.73 min of arc. Subjects performed the same two tasks as in experiment 1 in 10 repetitions for each of the three conditions in pseudorandom order.

3.2.4 *Apparatus.* The apparatus for displaying and viewing the stimuli was the same as in experiment 1.

3.2.5 *Procedure.* The subjects performed the same color-matching and boundary-strength rating task, and received identical instructions as in experiment 1.

3.2.6 *Results.* Figure 5 shows the results for the subjects' ratings in the second experiment. Ratings for perceived boundary strength decreased monotonically for each subject with increasing distance between line segments and flanks. The effect of gap size on the observers' ratings was significant in an ANOVA performed on the across-subjects data ($F_{2,147} = 128.2$, $p < 0.001$). Significant a posteriori Scheffé tests ($p < 0.001$) indicated that average ratings decreased from the no-gap to the small-gap condition, and from there to the large-gap condition.

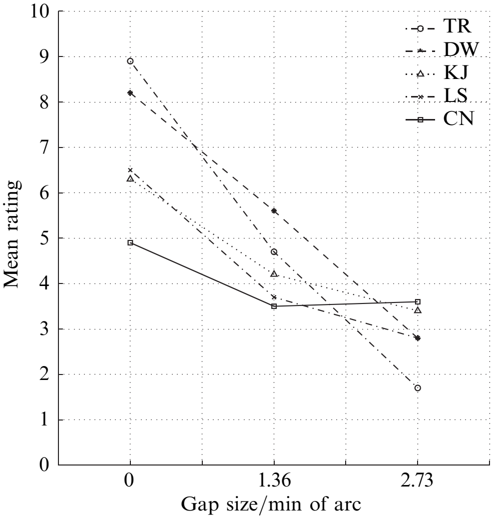


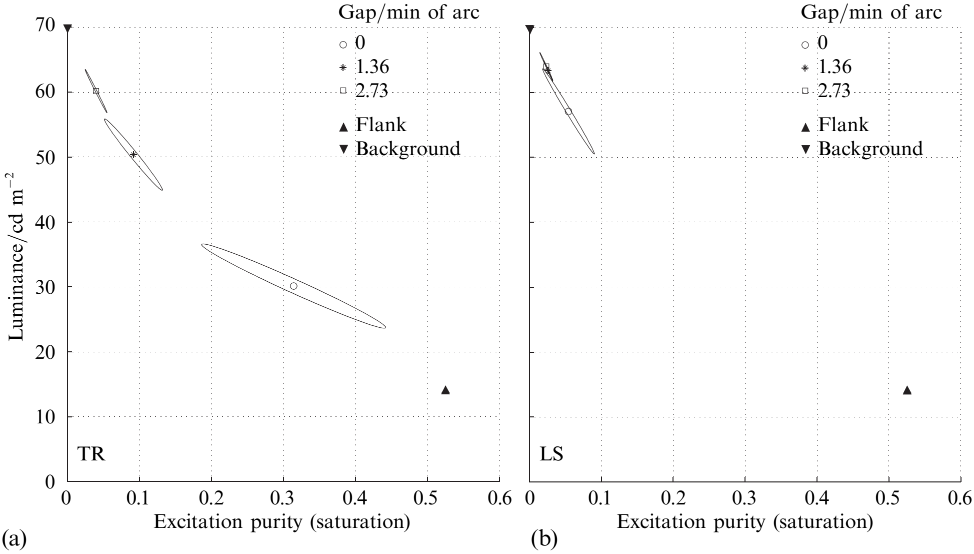
Figure 5. Mean boundary-strength ratings in experiment 2 for no gap, medium gap, and large gap between lines and flanks.

Regarding the color matches, the effect of increasing gaps between lines and flanks was similar to that of decreasing speeds in the first experiment: color spreading was impaired in four of the five subjects with the introduction of gaps (table 2). In these cases the disk appeared less saturated and lighter, as can be seen in figure 6, which shows data for two subjects. For one subject (CN), the matches did not substantially differ between conditions: they were all highly desaturated and close to background luminance. As for the other subjects, the matches resulting from the small-gap condition and the matches from the large-gap condition tend to lie close together, with highly desaturated settings near background luminance. In contrast, the matches resulting from the no-gap condition are separated considerably from this group in having more saturated and darker settings. The no-gap condition replicates the fastest condition (2.5 deg s^{-1}) of experiment 1, and each subject's settings and ratings show good reliability when compared between the two experiments.

3.2.7 *Discussion.* The results are similar to data obtained by Redies and Spillmann (1981) who showed how spatial discontinuities between the outer and inner cross in the modified Ehrenstein figure resulted in a loss of color spreading. For static displays of the watercolor illusion, Pinna et al (2001) demonstrated that color spreading vanishes quickly if flanks and lines are not immediately adjacent. Similarly, in our dynamic displays, color spreading persisted with larger gaps, but was greatly reduced in strength. As in experiment 1, the changes in the degree of color spreading covary with a reduction in perceived boundary strength, showing that the contours and surface color of the perceived layer together became less visible.

Table 2. Mean color matches (CIE x, y, L/cd m^{-2}) in experiment 2.

Subject	Parameter	Gap size/min of arc		
		0	1.36	2.73
TR	x	0.40	0.32	0.30
	y	0.32	0.31	0.31
	L/cd m^{-2}	30.1	50.4	60.2
DW	x	0.52	0.35	0.31
	y	0.34	0.32	0.31
	L/cd m^{-2}	17.8	41.7	59.0
KJ	x	0.59	0.47	0.46
	y	0.34	0.33	0.33
	L/cd m^{-2}	10.7	23.0	23.0
LS	x	0.31	0.30	0.30
	y	0.31	0.31	0.31
	L/cd m^{-2}	57.1	63.3	64.0
CN	x	0.31	0.30	0.30
	y	0.31	0.31	0.31
	L/cd m^{-2}	59.7	63.4	60.8



(a) (b)

Figure 6. Color matches and corresponding 95% confidence ellipses in experiment 2. (a) Observer TR. (b) Observer LS. See table 2 for data from the other subjects.

This experiment underlines the importance of figural determinants of color spreading, showing that spatial contiguity of line segments and flanks plays a critical role in flank-transparency displays. It also rules out simple spatiotemporal averaging processes as being the key influence for the color spreading since the number and summed length of red flanks was not affected by the experimental manipulations.

3.3 *Experiment 3: Spatial range of the color-spreading effect*

3.3.1 *Participants.* The same five subjects from the previous experiments also participated in experiment 3.

3.3.2 *Stimuli.* The stimulus was similar to the one in experiment 1, with the following differences: the line array was now rearranged such that all lines were vertical with a uniform distance to each other at all points (figure 2d). This was done in order to control for the exact distance to be bridged by the color spreading. The spacing between line segments varied from 0.89 to 1.84 deg between conditions. The size of the virtual disk was adapted accordingly, so as to keep the mean number of lines and flanks in the virtual disk constant over different spacings. The speed of the moving line segments was kept fixed at 2.5 deg s^{-1}, the speed we had found optimal in experiment 1 for creating a strong color-spreading effect.

3.3.3 *Design.* The independent variable in experiment 3 was distance between facing pairs of colored flanks in the interior of the virtual circle. The three levels chosen for the distance were 0.89, 1.43, and. 1.84 deg. In order to keep the number of flanks in the interior of the disk constant over levels of separation, the radius of the disk was adjusted to 1.27, 2.11, and 2.73 deg for the three distances, respectively. Observers performed 10 repetitions of the same tasks as in experiments 1 and 2 for each of the three conditions in pseudorandom order.

3.3.4 *Apparatus.* The apparatus for displaying and viewing the stimuli was the same as in experiments 1 and 2.

3.3.5 *Procedure.* The subjects performed the same color-matching and boundary-strength rating task, and received identical instructions as in experiments 1 and 2.

3.3.6 *Results.* Figure 7 shows the results for the subjects' ratings in experiment 3. Ratings for perceived boundary strength decreased monotonically for each subject with increasing distance between flanks attached to neighboring lines. The effect of line spacing on the observers' ratings was significant in an ANOVA performed on the across-subjects data ($F_{2,147} = 294.5$, $p < 0.001$). Significant a posteriori Scheffé tests ($p < 0.001$) indicated that average ratings decreased from each spacing to the next wider one.

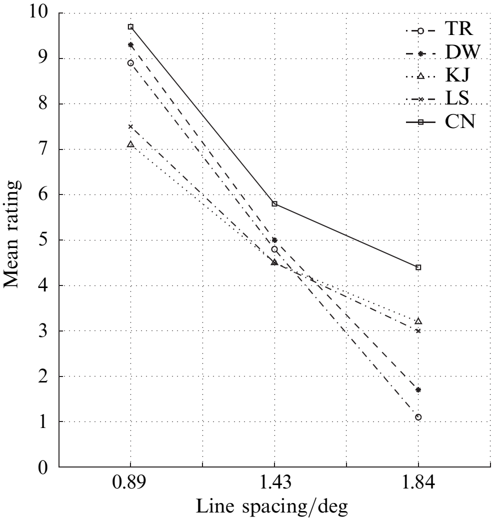


Figure 7. Mean boundary-strength ratings in experiment 3 for narrow spacing, medium spacing, and wide spacing of the lines.

The matching data from four of the five subjects show the same pattern as that obtained in experiments 1 and 2 with different manipulations: increasing the distance between line segments and thereby between pairs of opposing flanks leads to a reduction in color spreading in the sense that the illusory disk desaturates and becomes lighter (table 3, figure 8). Only for subject KJ did the illusory disk appear more saturated and slightly darker when seen in displays with greater separation between lines. Also evident from the data is the great dissimilarity between the settings for the nearest condition as opposed to the settings in the two other conditions, which for all

Table 3. Mean color matches (CIE x, y, L/cd m^{-2}) in experiment 3.

Subject	Parameter	Line spacing/deg		
		0.89	1.43	1.84
TR	x	0.46	0.30	0.30
	y	0.33	0.31	0.31
	L/cd m^{-2}	23.9	61.8	65.9
DW	x	0.36	0.30	0.29
	y	0.32	0.31	0.31
	L/cd m^{-2}	38.8	65.6	67.4
KJ	x	0.50	0.60	0.60
	y	0.33	0.34	0.34
	L/cd m^{-2}	16.4	8.8	7.8
LS	x	0.33	0.30	0.29
	y	0.31	0.31	0.31
	L/cd m^{-2}	46.9	65.8	66.8
CN	x	0.32	0.30	0.29
	y	0.31	0.31	0.31
	L/cd m^{-2}	46.8	63.5	66.1

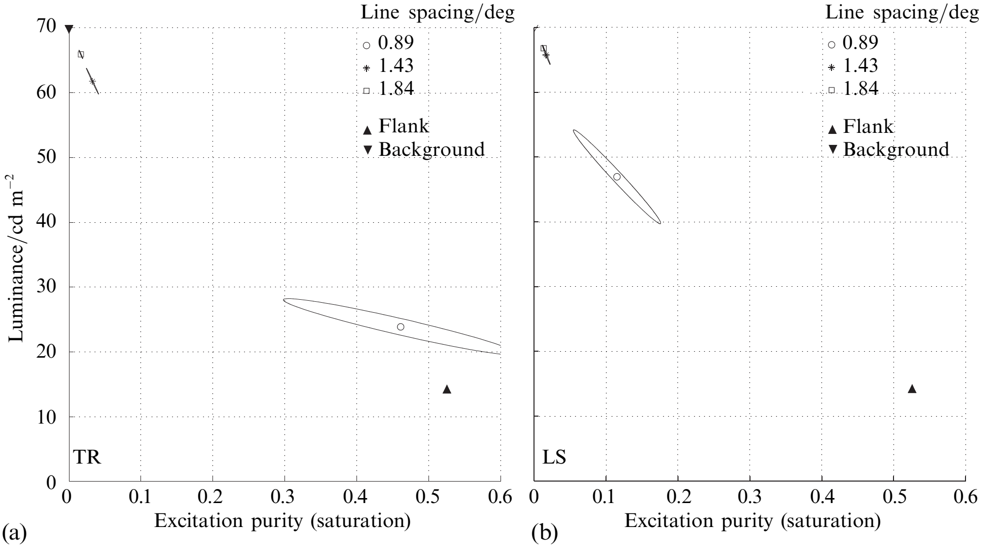


Figure 8. Color matches and corresponding 95% confidence ellipses in experiment 3. (a) Observer TR. (b) Observer LS. See table 3 for data from the other subjects.

observers lie close together. In particular, the settings for the two larger distances are close to the background white in four of the five subjects.

3.3.7 *Discussion.* Experiment 3 shows that the strength of the color spreading quickly degenerates as the spatial extent is increased over which the spreading must bridge. At larger distances, the color of the illusory disk is nearly identical to that of the background. As in the experiments before, the reduction in color spreading is expressed by increased luminance and reduced saturation in the color matches of the virtual disk. Except for subject KJ, a reduction in color spreading is correlated with weaker illusory contours defining the disk. Whereas Pinna et al (2001) reported that the watercolor effect could effectively operate over 45 deg visual angle, our display resembles more traditional displays of neon spreading which are greatly limited in the spatial extent covered by the spreading color.

4 Additional observations

While we made several design choices in the construction of our display—eg concerning the shape of background elements and of the virtual figure, or the direction of motion—the spreading effect does not depend much on this particular setup. Adding flanks to moving elements in a circumscribed region leads to color spreading much like other systematic element manipulations, such as changes in color or orientation (Cicerone et al 1995; Cunningham et al 1998; Shipley and Kellman 1993, 1994). As such, the structural layout of the flank-transparency display is easily generalized to other choices of inducing elements and virtual shapes, thus permitting studies on interpolation strategies of the visual system when facing arbitrary incomplete contours. For instance, the moving lines spread across the background can be replaced with small dots furnished with colored fringes when the dots are in the interior of the virtual shape. Likewise, substituting the virtual disk with a rectangular or concave shape is possible without altering the effect.

We concentrated on presenting results from displays that evoke a clear perception of color spreading and transparency. However, it should be noted that it is possible to generate structurally identical displays that fail to elicit such effects when colors for background, lines, and flanks are appropriately chosen. This occurs, for instance, with a greenish background (CIE $x = 0.35$, $y = 0.56$, $L = 10$ cd m^{-2}), light-gray lines (CIE $x = 0.29$, $y = 0.31$, $L = 15$ cd m^{-2}), and blue flanks of the same luminance as the background (CIE $x = 0.17$, $y = 0.15$, $L = 10$ cd m^{-2}). As is typically found in other displays, the perception of motion is strongly impaired near equiluminance of flanks and background. The flanks seem to move in discrete jumps, and no illusory boundaries are perceived. Pinna et al (2001) also reported degraded color spreading at equiluminance for watercolor-effect stimuli. It is thus evident that the color-spreading and transparency effects each depend on luminance conditions as well as on figural determinants.

Cicerone and Hoffman (1997) suggested that a functional advantage of color from motion might be a facilitation to detect moving camouflaged objects. They reported that objects which were invisible in still view could be perceived as moving behind a partially occluding screen in the apparent-motion condition. A very similar phenomenon can be observed in the flank-transparency display: given equally colored flanks and lines, a sufficient reduction of the width of the flanks in the interior of the virtual disk (eg to 1 pixel) can render the flanks virtually invisible in still view—only an array of uniform lines randomly spread over the background is perceived. When apparent motion is used, the disk surface defined by the presence of the narrow flanks immediately pops out. A similar salience enhancement due to static color spreading was reported by Redies et al (1984).(3) The disk also acquires a faint color unlike most demonstrations of motion-defined objects (see, eg, Regan 1986, 2000).

5 General discussion

As has already become evident in the introduction, there is much diversity in the phenomenology of color spreading and associated degrees of perceptual transparency. It has therefore been regarded an important undertaking to determine whether qualitatively different mechanisms give rise to the various types of color spreading or whether they are due to a combination of common underlying processes. Of particular interest is the question if there exists some shared rudimentary form of color spreading which is at the bottom of all phenomena, but which manifests itself in the guise of different perceptual interpretations depending on the stimulus class employed.

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(3) We thank one reviewer for pointing this out.

In the following discussion, we will first give a brief overview of selected models for transparent color spreading with a discussion of their applicability to our stimulus class and of their compatibility with our data (for a broader review, see, eg, Bressan et al 1997; see also Bressan 1997). We will then try to systematize the color-spreading phenomenology in terms of accordances and differences with respect to key qualities like transparency, spatial extent, and dependence on perceived depth order. Our goal is to evaluate the proposal of a common basal color-spreading effect whose final perceptual appearance may be modified through a limited set of structural stimulus characteristics.

5.1 *Models*

While some authors reason that qualitatively different mechanisms are responsible for the various color-spreading effects (Broerse et al 1999; Pinna et al 2001), others have attempted to conceptually integrate many of the phenomena in a single parsimonious theory. These theories mainly focus on the color determinants of spreading effects.

Bressan (1993b) proposes that "neon spreading and assimilation processes share the same low-level mechanism, and that the special sensory conditions for the occurrence of neon spreading are in fact the sensory conditions for the occurrence of perceptual transparency" (page 55). In this account, the diffusion component of neon spreading is entirely due to von Bezold-type assimilation (von Bezold 1874). The remaining phenomenal difference between pure assimilation stimuli and neon-spreading displays is then attributed to a layer decomposition of the assimilation color into a transparent filter and a background component in the case of neon spreading. The assimilation-based color filling-in is thus understood as a first processing stage. It is presumably followed by a layer decomposition if the stimulus structure present after the filling-in process meets the criteria for perceptual transparency. "Bezold-type assimilation turns into the neon spreading effect whenever (ie if and only if) it takes place within a surface that is also seen as transparent" (page 55). This approach denies extra theoretical relevance of the neon-spreading phenomenon beyond that of assimilation processes and transparency.

In contrast, Pinna et al (2001) object that their fringe-induced color spreading cannot be explained by assimilation effects since the latter are effective only over much smaller spatial extents than the illusory coloration observed in the watercolor effect. If one follows this argument and assumes a different underlying cause, then it seems possible as well to attribute the spreading component of neon color spreading to factors other than assimilation.

Anderson (1997) suggests a different mechanism for the illusory change in brightness that is observed in various displays, including achromatic versions of neon spreading. He argues that a "phenomenal scission of homogeneous luminance into multiple contributions" (page 419) gives rise to a change in brightness in order to reflect the inferred properties of the different contributing layers. This laminar segmentation (Mausfeld 1998) is presumably triggered by the presence of contour junctions between areas with different amounts of luminance contrast of the same polarity (see also Todorović 1997). While Bressan assumes that illusory spreading results from assimilation, and the neon effect from transparency, Anderson claims that changes in brightness as well as transparency simultaneously stem from perceptual scission into separate layers of the colored embedded elements.

In a strict sense, however, Anderson's reasoning seems to apply to those elements only, and therefore does not explicitly provide a mechanism for the characteristic brightness changes *in between* the embedded elements in neon-spreading displays. Also note that watercolor-effect stimuli lack junctions completely and thus are not easily explained by Anderson's approach.

In a general account of color and form perception, Grossberg and Mingolla (1985) discuss applications of their neuro-computational model to stimuli that elicit illusory contours and neon spreading (see, eg, Grossberg 1992, 1997 for further development of this idea into the FACADE model). They propose that a boundary contour system (BCS) and a complementary feature contour system (FCS) work as independent modes on extracting image properties. While the BCS serves to generate perceptual boundaries, the FCS creates information about the features (eg color or texture) that then fill in the regions defined by the BCS. Grossberg and Mingolla conjecture that in the case of neon-spreading displays, a local inhibition of the BCS output in the colored region can lead to a perceptual dispersion of color into the surround until it is 'stopped' by the next extracted contours.

Pinna et al (2001) demur that FACADE largely depends on the presence of line-end terminators which are not found in watercolor displays.

While the classical color-spreading demonstrations considered by all of the models require at least three colors to evoke the effect, we suggest that this is not an inherent characteristic of color spreading in general. The necessity to use three colors might instead be due to limitations imposed by the particular structural layout (insertion of colored elements in line drawings) shared by most known neon-color-spreading displays. Note that the Ehrenstein figure as well as most other static color-spreading demonstrations cannot separately specify figural stimulus composition on the one hand, and the colors of inducing pattern and colored shape on the other hand. For instance, identical colors of the inducing patterns and the inner cross in the modified Ehrenstein figure turn the image into one of a uniform cross—thereby crucially changing the object's composition of parts.

The necessary difference between inducing and embedded elements can also be sustained by means other than just color, as has been shown by Watanabe and Cavanagh (1991). If the inner cross of the Ehrenstein figure consists of a striped black-and-white texture, this texture seems to spread within the subjective contours of the disk. But in contrast with neon color spreading, it is not perceived as a transparent filter. Likewise, strong edge-induced texture spreading can be observed in dynamic flank-transparency displays when thin striped flanks are attached to the lines in the interior of the virtual shape instead of continuous flanks.

It is a common feature of the presented models of color spreading that—their differences notwithstanding—they all assume different relative contrasts between inducing pattern and background on the one hand; and between inserted colored elements and the background on the other hand as the initial trigger of the effect, ie assimilation, scission, or contour weakening. This approach necessarily fails to account for flank-transparency displays in which the same colors are used for both fringes and line segments—a setup that can induce a distinct impression of color spreading and transparency (Wollschläger et al 2001). Figure 9 illustrates this situation with a static display that leads to a slightly weaker effect than the dynamic version. Transparency in two-color stimuli was apparently first observed jointly by Kanizsa and Bozzi in 1960/1961 who later published an example quite similar to figure 9 (Bozzi 1975).(4)

If one tries to explain color spreading in two-color displays with assimilation processes, one faces the problem to specify the color conditions under which assimilation should not take place. This is a problem because, with respect to their color composition, two-color spreading displays are identical to the vast majority of two-color displays where no color spreading is observed.

With respect to transparency, the chromatic information present in a two-color flank-transparency display is no different from the usual case of a two-color display

(4) We thank one reviewer for mentioning this early example of perceptual transparency in two-color displays.

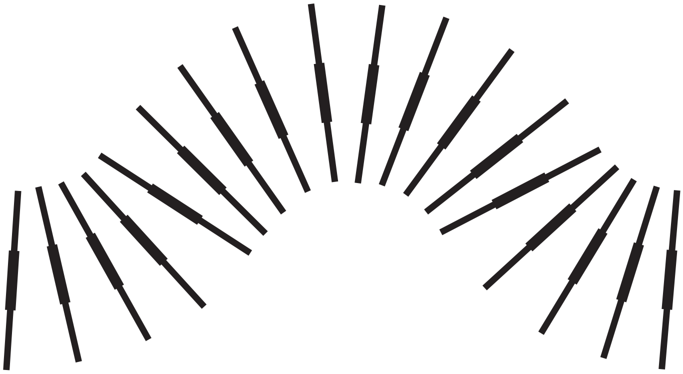

Figure 9. Static two-color display that exhibits color spreading.

that does not elicit transparency. Consequently, scission-based models of neon color spreading should make identical predictions for both cases, thus failing to explain the different phenomenology.

It is therefore clear that none of the models can be regarded as being sufficiently complete in specifying *necessary* conditions for the occurrence of color spreading and transparency.(5) The deficits of color-based models that become most apparent in the two-color case reveal the importance of other image characteristics in a cooperative cue-integration process leading to the final percept of color spreading.

5.2 *Systematizing the phenomenology*

The flank-transparency effect provides an important link between two different instantiations of color spreading: on the one hand the fringe-induced color spreading as presented by Broerse et al (1999) and Pinna et al (2001) with its pastel appearance and long-range operation; and on the other hand traditional, neon-like color spreading that appears transparent. We were able to show in the present experiments that stimuli similar to watercolor-effect displays behave like neon-spreading stimuli once apparent motion is introduced to provide figural cues for the presence of an object. Instead of looking matte and opaque, the color spreading now appears transparent and is bounded by subjective contours—another typical feature of classical neon spreading that is absent in the watercolor effect. As shown in the present experiments, flank transparency shares its dependence on apparent motion with color-from-motion displays devised by Cicerone and Hoffman (1992), as well as its connection between perceived boundary strength and amount of color spreading. It is also similar to classical neon spreading in the characteristic short-range operation demonstrated in experiment 3.

We propose to analyze the wide-ranged phenomenology of color spreading in terms of a cue-integration process which can dynamically turn the generic, intangible color spreading of the watercolor effect at the one end of the phenomenological continuum into that of a transparent surface at the other end. We propose that one set of cues likely to be involved are those which specify the degree of objecthood of the virtual shape, eg dynamic grouping information or Gestalt principles of perceptual organization (Palmer 1999). By 'objecthood' we mean the distinctness or definedness of a perceptual entity. This line of thought is similar to Bressan's conjecture (1993a, 1993b) about the intrinsic connection between color assimilation and transparent, neon-like color spreading. But whereas Bressan assumed that a basic color assimilation phenomenon leads to perceptual transparency exactly when the color conditions for transparency are met, we suggest that a more complex cue-integration process is happening which might fruitfully be analyzed in a theoretical context which is object-creation based.

(5) It should be noted that Anderson explicitly refrains from making this claim.

Evidence for our conjecture that the different phenomenology of color spreading stems in part from varying degrees of object distinctness comes from research on the influence of depth perception on color spreading and transparency (Anderson 1997, 1999; Nakayama et al 1990). A position in the depth order of the scene is a phenomenological quality which perceptually well-defined objects usually possess. Cicerone et al (1995) reported that in color-from-motion displays the depth localization of the virtual disk was more pronounced if the color spreading was stronger. The same impression of a clear surface stratification is present in most static neon-color-spreading displays. Bressan (1993a, page 360) also stresses the importance of "perceptual detachment of the induced color from the plane of the figure" for neon color spreading. It can even be shown that in some cases color spreading critically depends on the perceived depth order (Nakayama et al 1990).

In contrast, Pinna et al (2001) note that the watercolor effect is not affected by such manipulations. We propose that this occurs because color spreading in the watercolor effect is not attached to an object that is different from the surface as defined by the real colored boundaries. Hence, the color spreading does not qualify as a separate object, and therefore lacks typical object features like depth stratification. A flank-transparency display taps the edge-induced color spreading of the watercolor effect, but it also forces the creation of subjective contours which define a separate object containing the spreading. This seems to be achieved by two mechanisms: on the one hand, dynamic boundary formation (Cunningham et al 1998) signaled by regular spatiotemporal patterns of change resulting from the dynamic structure of the display; and, on the other hand, the endpoints of the attached flanks creating L-junctions. This latter static cue, which is absent in the watercolor effect, was found to be a potent trigger for perceptual surface completion (Rubin 2001). Once objecthood of the virtual shape is established, color spreading becomes a surface attribute with all its consequences. Because it does not occlude objects from the background as, eg, in dynamic occlusion stimuli, it appears transparent—as long as it does not contradict color conditions for perceptual transparency.

A similar transformation between object-like transparent color-spreading stimuli and unspecified, 'generic' color spreading was described by Watanabe and Sato (1989) for the equiluminant Ehrenstein figure, and by Miyahara and Cicerone (1997) for equiluminant color-from-motion displays: a murky spreading of color was seen when all colors in the display were of common luminance. The authors note that at equiluminance there were no illusory contours for the color to spread out to, and the color seemed to diffuse a certain distance and then fade out. In contrast to non-equiluminant conditions, the color spreading thus is not seen as belonging to a transparent filter or as specifying an amodally completed object, such as a full disk behind an aperture (Michotte et al 1894). Correspondingly, the color spreading is not seen in front of the other image elements (transparency interpretation) or behind them (amodal completion).

6 Conclusions

We performed three experiments to explore the psychophysical effects of speed, gap size between lines and flanks, and line spacing in dynamic flank-transparency displays. Experiment 1 shows that the flank-transparency effect benefits—in the range we explored—from increased speed of the virtual shape: the illusory color becomes more saturated, and this effect is paralleled by an increasing perceptual clarity of the shape's illusory boundaries. Experiment 2 underlines the fact that flank-transparency displays are sensitive to the spatial contiguity of their elements. Gaps between inducing lines and flanks quickly lead to a degradation of the color-spreading effect. Again, the change in color-spreading perspicuity covaries with the change in boundary strength.

Experiment 3 shows that the flank-transparency effect works best over short distances and monotonically decreases with wider line spacing.

These findings reveal great similarity between flank-transparency displays and classical neon-color-spreading effects, be they static or dynamic. This result provides a phenomenological connection between fringe-induced spreading effects and classical neon-color-spreading stimuli, which in their original form are dissimilar in important respects. We posit that this connection suggests a role for object-creation processes in the emergence of neon color spreading, although further experiments are needed which directly address this hypothesized link.

As is shown most directly in the case of a two-color display, current approaches to color spreading are inadequate to account for flank transparency. Their color conditions can be effectively bypassed or rendered less influential if additional cues favoring a transparency interpretation are strong enough. Without specifying the origin of color spreading itself, we argue that it can be treated in its pure form as a generic fundamental effect which can be developed by the visual system into different object qualities as indicated by the presence of various color and objecthood cues. Incorporating into Bressan's (1993a, 1993b) view of the connection between color spreading and transparency a more general notion of cue integration leading to the construction of objects might lead to a general framework for analyzing a wide variety of color-spreading phenomena.

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