Dynamic Flanking Illusion:
Color Spreading and Transparency

Daniel Wollschläger Antonio M. Rodriguez Donald D. Hoffman

Department of Cognitive Sciences
University of California at Irvine

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Abstract

We analyze a new dynamic color spreading display created by adding narrow colored flanks to rigidly moving black lines whenever the lines fall in the interior of a stationary imaginary disk (Wollschläger et al, in press). This setup induces the perception of a colored transparent filter bounded by strong illusory contours hovering over the moving line array. We performed three experiments to quantitatively study the enhancing effect of apparent motion, the spatial extent of the color spreading, and the effect of introducing small spatial discontinuities (gaps) between lines and flanks. Results serve to range in the new illusion in the context of known color spreading effects. The manifest enhancing dynamic properties of the stimulus point to possible interactions between the processing of color and motion in surface construction.

1 Introduction

Neon color spreading refers to the perceptual phenomenon of color seemingly dispersing from image elements into their surround, thereby giving it an ethereal neon–like veil. The observed coloration overcomes 'real' figure boundaries and typically covers an area confined by a subjective contour. Figure 1a illustrates this effect with a display similarly to many classical color spreading stimuli, such as the modified Ehrenstein figure (Redies & Spillmann, 1981). A pattern of vertical black lines is placed on a white background. Colored elements are inserted such that each line consists of three segments—two black outer segments connected by a short blue inner segment. This setup results in the perception of a continuous glowing–blue horizontal band lying on top of the black bars. The display shares typical perceptual characteristics with other color spreading demonstrations, such as perceptual transparency, illusory contours and a desaturation of the spreading color compared to an isolated view of the colored elements alone (figure 1b).

While we will argue that the phenomenon of color spreading was likely to be known and systematically exploited for practical use as early as during the 16^{th} and 17^{th} century, first scientific accounts were given by Wallach (1935), Varin (1971) and van Tuijl (1975). Other classes of stimuli which differ in certain respects from these classical displays, have been shown to elicit some form of color spreading, as well:

Color–from–motion displays created by Cicerone & Hoffman (1991, 1992; Cicerone et al, 1995) and Shipley & Kellman (1993, 1994) use apparent motion as a way to induce the perception of subjective contours which are filled with color diffused from stimulus elements lying in the interior of a motion–defined virtual disk. In this particular kind of display, apparent motion was shown to be required in order to perceive the color spreading effect. Furthermore, the strength of the color spreading effect was modulated by the amount of perceived motion in the display.

A class of static stimuli devised by Redies & Spillmann (Redies & 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. Redies et al (1984) propose that this 'neon flanks' phenomenon can be taken as a basic local effect which in accumulation serves to elicit the global neon spreading observed in appropriately constructed displays. Based on their findings on fringe–induced color spreading in the McCollough effect (McCollough, 1965), Broerse et al (1999) 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.

Figure 1c illustrates how global color spreading can be achieved by just changing the colors at edges of the inducing pattern—this alone can suffice to generate neon spreading covering longer distances. E.g., eliminating most of the colored area of figure 1b—leaving behind only thin segments at the lines' edges—does not substantially impair the color spreading effect. The crucial role of the edge information relates this kind of display to the Craik–O'Brien–Cornsweet illusion (Todorovic, 1987; Grossberg & Todorovic, 1988; Davey et al, 1998), and to other filling–in phenomena (see e.g. Yarbus, 1967).

Pinna & Spillmann (2001) argue that in their similarly constructed "watercolor effect" displays (Pinna, 1987; Pinna & Spillmann, 2001), the perceived 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. Pinna & Spillmann report that in their case no transparency is observed, a characteristic that is shared by most classical neon color spreading displays (Bressan et al, 1997). Based on their observations, they argue that the watercolor effect can neither be explained by von Bezold (1874) nor Helson–type (1963) assimilation, nor does it resemble "other kinds of assimilation such as neon color spreading" (p. **).

Pinna & Spillmann (2001) highlight the ability to influence figure–ground segregation as a possible functional aspect of the watercolor effect. Taken together with the considerable spatial extent of the color spreading, this likely offers some insight in coloring techniques used by Renaissance map makers during the late 16^{th} and the 17^{th} century. In some maps from this epoch, regions are painted in outlines only with flanking colored lines alongside them (figure 3). This 'bordercolor technique' is prominently featured e.g. in Joan Blaeau's maps (Shirley, 1983; Bagrow & Skelton, 1985). The result is a layout being strikingly similar to watercolor effect stimuli. Map makers evidently employed color spreading effects in a systematic way to ensure that land appears as figure, and countries are easily silhouetted against each other without having to be drawn in solid colors. Although the induced color spreading has to 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]

The fact that in many displays, the region encompassed by color spreading appears—albeit sometimes faintly so—as a transparent layer, has been noted early on **(some lit)** and has subsequently drawn considerable

[1] Pinna & Spillmann indeed hint at a possible application in map–making (p. **), but they do not elaborate further on this thought.

attention to it (Nakayama et al, 1990; Bressan, 1993b; Bressan et al, 1997; Ekroll & Faul, submitted). However, the intrinsic relationship between both phenomena remains a debated issue. In the dynamic flanking illusion, observers consistently report that perceptual transparency coincides with color spreading.

2 Models

There evidently 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 theoretically different mechanisms give rise to this variety or whether it is due to a combination of common underlying processes. While some authors reason that qualitatively different mechanisms underlie the various color spreading effects (Broerse et al, 1999; Pinna & Spillmann, 2001), others have attempted to conceptually integrate many of the phenomena in a single parsimonious theory. We will give a brief account of selected proposed models of the latter kind with a discussion on applicability to our stimulus class (for a broader review, see e.g. Bressan et al, 1997; see also Bressan, 1997).

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” (p. 55). In this account, neon spreading and von Bezold–type assimilation phenomena would be distinguished only by a layer decomposition of the assimilation color into a transparent filter and a background component in the case of neon spreading. “Bezold–type assimilation turns into the neon spreading effect whenever (i.e., if and only if) it takes place within a surface that is also seen as transparent.” (p. 55) This approach denies extra theoretical relevance of the neon color spreading phenomenon beyond that of assimilation processes and transparency (p. 63).

Anderson (1997) suggests a different mechanism for the occurring change in perceived luminance that is observed in various brightness illusions, including achromatic versions of neon spreading. He argues that a “phenomenal scission of homogeneous luminance into multiple contributions” (p. 419) gives rise to a change in perceptual luminance 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 luminance as well as transparency simultaneously stem from perceptual scission of the image into separate layers.

Ekroll & Faul (submitted) show that Anderson’s approach is compatible with a class of transparency models descending from Metelli’s (1970) episcotister model. These models (see e.g. Da Pos, 1989; D’Zmura et al, 1997; Faul, 1997) generalize Metelli’s framework to the case of color transparency, thus making them—in a modified form—applicable to neon color spreading. Ekroll & Faul demonstrate that the color conditions for the occurrence of perceptual transparency in dynamic neon spreading displays can be well accounted for in this way.

In a general account of color and form perception, Grossberg & Mingolla (1985) discuss applications of their neuro–computational model to stimuli that elicit illusory contours and neon spreading (see e.g. 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 (e.g., color or texture) that then fill in the regions defined by the BCS, as it were. Grossberg & 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.

Bressan (1993a) re–analyses results obtained by Ejima et al (1984) regarding the dependence of color spreading in the modified Ehrenstein figure on the spectral composition of light coming from it in terms of these parallel working systems. In particular, she cites complementary color spreading initiated by a weakening of the cross' edges caused by the inducing pattern as being responsible for the observed dependence of spreading strength on the combination of colors of inducing pattern and inner cross. The idea of complementary spreading leads her to the prediction that "the effect should be weakest (or disappear altogether) when the colours of the mixture are complementary to each other. This is the case when the pattern and the cross have the same (or similar) colour" (p. 376). In this case, the complementary color of the inducing elements would exactly cancel that of the inner shape in a color–opponent processing stage. Ejima et al (1984) indeed report weak spreading in the case of similar colors.

3 Dynamic flanking illusion

The dynamic flanking illusion obtains from combining dynamic color spreading (see e.g. Cicerone et al, 1995) with Pinna's (1987; Pinna & Spillmann, 2001) watercolor effect. The display contains a virtual disk moving 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 quadratic grid, and their orientation is pseudo–random. All line segments have the same color as each other, but different from the uniformly–colored field. A horizontally and vertically centered virtual disk is then defined. The line segments are rigidly translated a slight amount to the right in each frame, and narrow colored flanks are added collinear to those lines that fall in the interior of the virtual disk (figure *). 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]

For conducting the experiments, 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 used for doing color matching, or a number reflecting the subject's rating choice. The background of the bottom half was uniform and of the same color as the background in the top half.

In preliminary studies we found this display equivalent to one with a static background and a moving virtual disk. However, keeping the disk stationary has several advantages: The display allows for a fixed eye position, thus avoiding potential effects of smooth–pursuit eye movements. A fixation cross was placed on the horizontal center line at an eccentricity of 2° to the disk boundary, as our studies had indicated that the effect was stronger under parafoveal viewing conditions. Color–matching tasks seem to benefit from a stationary disk, as we had

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

found the comparison between static objects easier to perform than between moving objects. Furthermore, by using an illusory half–circle in the top half of the display and a complementary solid half–circle in the bottom half, the display closely mimics conventional color matching setups.

4 Experiments

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

Experiment 1 studies the influence of apparent motion on perceived brightness and saturation of the virtual disk, as well as on perceived strength of its boundaries. We observe that . . . Results are compared to those by Cicerone et al (1995), obtained in a similar task. In experiment 2 we determine the relationship between observers' color matches and the amount of separation between inducing black lines and colored flanks. We show that . . . . Results are related to findings in comparable experiments about color spreading in the Ehrenstein figure (Redies & Spillmann, 1981). Experiment 3 estimates the spatial extent over which color spreading can operate in our display. We obtain a measure for spatial drop–off and compare it to that of other neon spreading displays. Results indicate that . . .

The observers' task in a given trial was twofold in all experiments performed. First, observers matched the color of the virtual disk in the upper half of the screen by adjusting the color of a solid half–circle in the lower half. Pilot studies had indicated that perceived hue of the target disk was not affected by the experimental manipulations, so we restricted the subjects settings to changing luminance and saturation in a Hue Saturation Brightness color space. This helped reduce the complexity of the color–matching procedure and increase reliability. All subjects received prior training in adjusting the color in a 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. 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 scale's possible range, using several well–known examples of illusory figures with different boundary strengths.

4.1 Experiment 1: Velocity of moving lines

Apparatus and subjects The stimuli were displayed on an Apple Studio 17 inch color monitor using the OpenGL library. The monitor was calibrated for displaying color stimuli using a Spectracolorimeter (Photo Research, PR–650). Observers saw the display in a dark room at a distance of 80cm in normal viewing conditions. Four observers with normal or corrected to visual acuity participated in the experiment, among them two of the authors. Normal color vision was ensured using Rayleigh matches with a Neitz anomaloscope.

Method The display's background was white with CIE 1931 (Wyszecki and Stiles, 1982) coordinates $x =$, $y =$, $Y =$, and comprised a visual angle of $15°$. The display was bipartite, the upper half contained the dynamic color spreading stimulus, the lower half the figures used for the described matching and rating tasks.

The dynamic stimulus was such that it contained vertical black lines (CIE $x =$, $y =$, $Y =$) of width $0.2°$ and length $4.5°$, separated by $0.2°$. Red (CIE $x =$, $y =$, $Y =$), and in a separate session green (CIE $x =$, $y =$, $Y =$) flanks of $0.05°$ size were added collinear to the lines on both of their long sides in the interior of a virtual half–circle with a radius of $2.5°$. The line array rigidly moved at speeds varying from $0.5°/s$ to $2.5°/s$ to the right with the virtual half–circle remaining stationary at the center of the screen.

In the first task, a solid complementary half–circle for the color matching was displayed in the lower half of the screen on the same white background as the upper half, separated by $0.2°$ from the virtual half–circle. In the second task, the screen displayed a number corresponding to the observer's rating choice entered on the keyboard.

Procedure The independent variable was speed of the moving line array. The display was presented using one of three different velocities, $0.5°/s$, $1.5°/s$, and $2.5°/s$. Subjects performed the three tasks with 10 repetitions for each of the three speed levels in pseudo–random order.

Results

4.2 Experiment 2: Modulating gap size

Apparatus and subjects The apparatus for displaying and viewing the stimuli was the same as in Experiment 1.

Method The stimulus used was the same as in experiment 1 with the difference that gaps of varying size were introduced between the colored flanks and the line segments. Gap size ranged from * min of arc to * min of arc. The speed of the moving line segments was kept constant at $2.5°/s$, the speed we found optimal in experiment 1 for creating a strong color spreading effect.

Procedure The independent variable was size of the gap introduced between the colored flanks and the line segments (figure *). The three gap sizes employed were no gap, *, and * min of arc. Subjects performed the three tasks in 10 repetitions for each of the three conditions in pseudo–random order.

Results

4.3 Experiment 3: Spatial range of the color spreading effect

Apparatus and subjects The apparatus for displaying and viewing the stimuli was the same as in Experiments 1 and 2.

Method 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. This was done in order to control for the exact distance to be bridged by the color spreading. The spacing between line segments varied between 12 min of arc and 20 min of arc between conditions, the size of the virtual disk being adapted accordingly so as to keep the number of lines and flanks in the circle constant over different amounts of separations. The speed of the moving line segments was kept constant at $2.5°/s$, the speed we found optimal in experiment 1 for creating a strong color spreading effect.

Procedure The independent variable was distance between facing pairs of colored flanks in the interior of the virtual circle. The three levels chosen for the distance were *, *, and *. 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 *, *, and *, for the distances of *, *, and *, respectively. Observers performed 10 repetitions of the three tasks for each of the three conditions in pseudo–random order.

Results

5 Casual observations

While we made several "design choices" in the construction of our display, e.g., concerning the shape of background elements and the virtual figure, or the direction of motion, the neon spreading effect does not depend on the particular setup. Adding flanks to moving elements in a circumscribed virtual region acts very much like other systematic element manipulations, such as changes in color or orientation (Shipley & Kellman, 1993, 1994; Cicerone et al, 1995; Cunningham et al, 1998). E.g., the moving lines spread across the background can be replaced with small dots that attain colored flanks parallel to their own contour in the interior of the virtual shape. Likewise, substituting the virtual disk with a rectangular or concave shape is possible without altering the effect.

Cicerone & Hoffman (1997) suggested that a functional advantage of the color from motion effect might be a facilitation in detecting moving camouflaged objects. They reported that objects could be perceived as moving behind a partially occluding screen in the apparent motion condition that were invisible in still view. A very similar phenomenon can be observed in the dynamic flanking display: With equal colors of flanks and lines, a sufficient reduction of the width of the flanks in the interior of the virtual disk (e.g. to 1 pixel) can render the flanks invisible in still view. An array of uniform lines randomly spread over the background is perceived. Using apparent motion however, the disk surface defined by the presence of the narrow flanks immediately pops out. This detection facilitation holds even after removing every second flank from the lines in the interior of the virtual shape as to further reduce the absolute area defining it.

6 Discussion

We introduced a new dynamic color spreading display that demonstrates how to achieve a strong spreading effect suitable for quantitative matching tasks by combining colored flanks and apparent motion. The structural layout of the 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.

We suggest that this is not an inherent characteristic of color spreading in general, but might be due to limitations imposed by the particular structural layout (insertion of colored elements in black patterns) shared by most known neon spreading displays. Note that the Ehrenstein figure as well as most other static color spreading demonstrations lack the ability to separately specify figural stimulus composition on the one hand, and the colors of inducing pattern and colored shape on the other hand. E.g., identical colors of the inducing pattern and the inner cross in the modified Ehrenstein figure turn the image into one of a bigger uniform cross—thereby crucially changing the display's composition of objects. The same geometric limitation persists in other static demonstrations, rendering them inappropriate for studying the condition of similar or identical colors due to the confoundation of image characteristics. We have previously shown (Wollschläger et al, submitted) how color spreading and perceptual transparency strongly occur in the dynamic flanking display using identical colors for line segments and flanks such that only two colors are present in the stimulus. In this case, the perceived spreading color is a desaturated version of the color used for line segments and flanks—not its complement. We will elaborate on this result with quantitative methods in the reported experiments.

It is a common feature of all presented attempts to model color spreading that—their differences notwithstanding—they similarly assume some relative difference between inducing pattern and inserted colored element to the background as the initial trigger of the effect (i.e., assimilation, scission, contour weakening). This approach necessarily fails in our two–color display. Furthermore, theories that predict complementary spreading followed by color mixture as the basic mechanism are at odds with the observations given in the dynamic flanking illusion. Another shortcoming of the presented models seems to be their disregard of temporal characteristics in color–from–motion displays. As such, they fail to account for the enhancing and in some cases indispensable role of motion for the occurrence of color spreading.

Assimilation: Unlikely due to long spatial distance covered. Probably true for other spreading types, as well. (Pinna & Spillmann)

7 Conclusions

Three experiments have been performed: Experiment 1 shows that . . . Experiment 2 underlines the fact that . . . Eperiment 3 compares the . . .

Continuity in perception -> continuity in model

We found that the enhancing effect of apparent motion makes quantitative color matching tasks easier to perform compared to static stimuli, which often have a slightly ethereal quality and are perceptually instable.

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