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Surface color from boundaries: a new 'watercolor' illusion

Baingio Pinna [a,*], Gavin Brelstaff [b], Lothar Spillmann [c]

[a] *Department of Human Sciences and Antiquities, University of Sassari, Piazza Conte di Moriana, 8, I-07100, Sassari, Italy*
[b] *Center for Advanced Studies, Research and Development, ZI Macchiareddu, CP94, I-09010 Uta (Cagliari), Italy*
[c] *Brain Research Unit, University of Freiburg, Hansastrasse 9, D-79104 Freiburg, Germany*

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Abstract

A colored line flanking a darker border will appear to assimilate its color onto the enclosed white area over distances of up to 45 deg (the Watercolor Effect). This coloration is uniform and complete within 100 ms. We found that thin (6 arcmin), winding inducing lines with different contrasts to the ground are generally more effective than thick, straight, and equiluminant lines. Blue and red lines induce the strongest effects, but watercolor spreading may also be seen with green and yellow. On a white background, color spreading is stronger than on chromatic, gray or black backgrounds. Little or no color is perceived when a narrow white zone (gap) is inserted in between the two inducing lines. However, chains of colored dots instead of continuous lines suffice to produce spreading. Edge-induced color is also observed when the two colored lines are presented dichoptically, suggesting a cortical origin. The Watercolor Effect described here may serve to enhance figure–ground segregation by imparting surface color onto the enclosed area, and to promote grouping between distant stimulus elements. As a grouping factor, watercolor coloration wins over proximity. Assimilative color spreading may arise in two steps: First, weakening of the contour by lateral inhibition between differentially activated edge cells (local diffusion); and second, unbarriered flow of color onto the enclosed area (global diffusion). © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Assimilation; Edge induction; Filling-in; Long-range interaction; Watercolor effect

1. Introduction

If you want to paint an island on a map, do you need a whole lot of paint or will a little do as well? We contend that it is sufficient to just paint a dark border, flank it by a colored line, and leave the filling-in of color to the brain. The Watercolor Effect presented in Fig. 1 strikingly demonstrates the power of long-distance spatial induction by color spreading from simple inducing lines. The pattern shows a thin purple border delineating a series of ragged surfaces on a white background. Accompanying that border is an orange fringe of similar width flanking it on one side. The surfaces abutting that line no longer look white, but instead look subtly and uniformly tinted by the color of the flanking line. In comparison, the surfaces abutting the purple line look a cold white. Whereas the orangish surface has the appearance of a figure, the white surface on the other side is perceived as ground. Blue, red, and green figures may also be produced in this manner.

The Watercolor Effect was first demonstrated by Pinna (1987) who observed that the surface appeared to assume the color attribute of the line that abuts it. Clearly, its spatial extent is much larger than, and different from, the narrow undulating spaces in von Bezold (1874) arabesques (for reproductions of these patterns, see Evans, 1948), the somewhat wider assimilation observed in the pincushion illusion (de Weert, 1991; de Weert & Spillmann, 1995), or the neon flanks bridging the gap between collinear black inducing lines in the Ehrenstein figure (Redies & Spillmann, 1981; Redies, Spillmann, & Kunz, 1984).

Recently, fringe-induced color spreading has been described, for narrow grating bars, by Broerse, Vladusich, and O'Shea (1999) in conjunction with the McCollough effect (McCollough, 1965).They interpret their data in terms of chromatic aberration as it occurs when

* Corresponding author. Tel.: +39-79-229705; fax +39-79-229619.
E-mail address: baingio@ssmain.uniss.it (B. Pinna).

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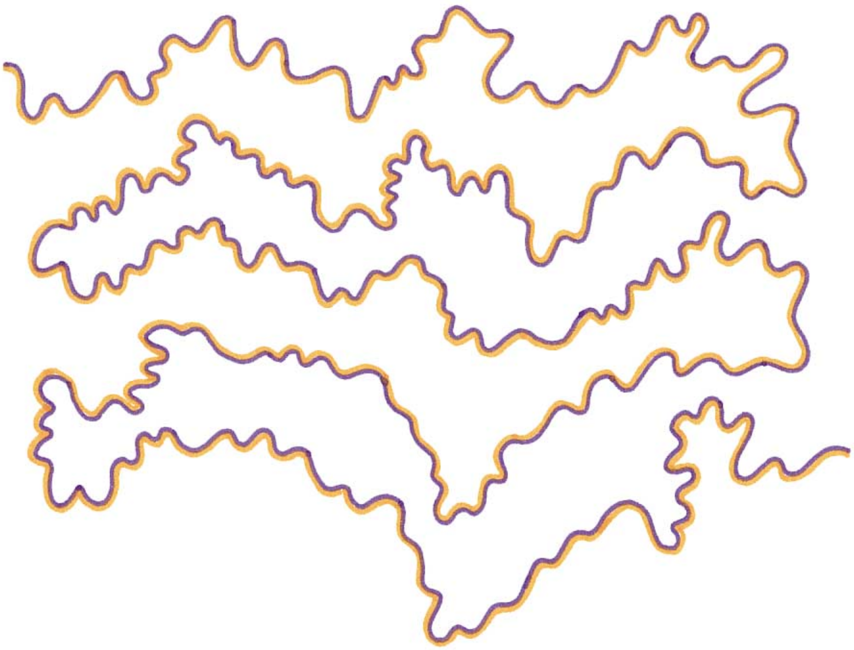


Fig. 1. The Watercolor Effect as an example of surface color arising from thin boundaries. The figure shows a winding purple border delineating an enclosed white area. On the inside of the purple border runs an orange flanking line. Note that an area needs to be well flanked at least on two sides to produce a substantial effect.

looking through prisms (Kohler, 1962). However, the spreading effect in our stimuli persists even when observed through an achromatizing lens, suggesting that it is not due to chromatic aberration. We therefore think that the Watercolor Effect described here is a phenomenon of its own, best accounted for by edge-induced long-range interactions due to cortical processing.

2. Methods and results

2.1. Distance of color spreading

To determine the largest surface over which color spreads, we used 25 stimuli of different dimensions (topologically equivalent to Fig. 1), with their short axes ranging from 2.9 to 58.1 deg (step size 2.3 deg). A large sheet of white paper, 82×100.4 deg, served as a background. Stimuli were hand-drawn with a purple magic marker for the outside border and an orange magic marker for the inner fringe.[1] The purple/orange color pair was chosen because it produced a clearly visible assimilation effect. Line width was 6 arcmin in each case. Stimuli were presented in the frontoparallel plane, 50 cm away from the eyes, with the fixation point centered on the upper boundary of the middle lobe. Ambient illumination in the room was 250 lux. Eleven undergraduate students naïve to the purpose of the experiment participated. Subjects first familiarized themselves with the watercolor phenomenon before performing the actual test. A chin–forehead rest was used for observation. Each stimulus was presented once, in a random order. The task was to report whether or not there was color spreading and whether it was uniform all over the enclosed area. There was no time limit, and responses were prompt. We found that the number of subjects reporting color spreading decreased with increasing length of the short axis of the stimulus lobes. A threshold was reached when the height of the enclosed surface area exceeded a visual angle of 45 deg.

2.2. Exposure duration

We further attempted to measure the shortest time required for watercolor to spread on a 30 deg (short axis) version of Fig. 1, using an electromagnetic shutter in front of one eye (monocular observation). Three trained observers served as subjects. Uniform coloration was perceived within 100 ms, the shortest exposure duration available. Spreading appeared to be effectively instantaneous, i.e. there was no perceptible propagation of color from the edge under these conditions.

[1] Illusory stimuli may also be produced on the face of a computer monitor, but figures drawn on paper proved more practical to use in this initial study of the watercolor phenomenon.

2.3. Line thickness

Next, we determined the optimal line thickness for eliciting watercolor spreading. This was done by varying the thickness of both the purple border and the orange fringe in the stimulus pattern depicted in Fig. 1, while keeping the stimulus at the same distance as before (50 cm). Four line widths (6, 12, 18, and 24 arcmin) were tested once in a random order using magnitude estimation. The background size was 31 × 22.7 deg. A reference figure (line width 6.0 arcmin) with color fringes added to the inner edges served as the upper anchor (rating value 7), while the same figure, however, without color fringes, served as the lower anchor (rating value 1). Both anchor values could be exceeded. Eleven new subjects participated. They were instructed to compare the strength and uniformity of the color spreading in the test figures with those in the two reference figures (which were always shown). On average, color spreading was strongest (rating value of 6.9) when each of the inducing lines subtended a visual angle of 6.0 arcmin. With increasing line width, the rated strength of the effect decreased ($F_{3,40} = 34.4$, $P < 0.0001$). An optimal width of 6 arcmin for color spreading was also obtained using the method of limits. Here, subjects walked towards and away from the figure signaling when the watercolor was strongest. The grand mean of ascending and descending measurements was taken as a measure of optimal line thickness and converted to visual angle. Note that this procedure implies a co-variation of the area enclosed between the inducing lines.

2.4. Waviness

An obvious question is whether or not the inducing lines need to be *winding* to elicit watercolor spreading. To answer this question, magnitude estimation was again used. A stimulus pattern similar to Fig. 1 served as the upper modulus (magnitude 7), while the same pattern with a purple border, but no orange flank, served as the lower modulus (magnitude 1). Six stimuli drawn on white paper, 21.7 × 33.4 deg in size, were used. The borders were sinusoidally modulated at spatial frequencies of 0.2, 0.4, 0.6, 1.03, or 1.23 cycles/deg and a peak-to-trough amplitude of 0.57 deg. Additionally, a pattern with straight lobe sides was used. Stimuli were presented once in a random order. Ten new subjects participated in the experiment. Results show that the strength of color spreading increases monotonically with increasing spatial frequency of the sinusoidal modulation. Ratings for the five sinusoidal stimuli differed significantly from each other ($F_{5,54} = 7.611$, $P < 0.0001$). All subjects reported strong watercolor spreading also for the stimuli having straight borders (the mean rating value was 4.5), although the effects elicited by sinusoidally winding inducing lines were superior in strength.

2.5. Inducing color

We also tried different combinations of inducing colors. Lines were again hand-drawn using felt pens.[2] Magnitude estimation was used as before. The upper anchor ('7') was a figure with a black contour and a light gray fringe, whereas the lower anchor ('1') was the same figure with just the fringe (i.e. no contour). Pairs of blue, green, yellow, and red lines were presented in a random order, and each pair of colors was judged once. Ten new subjects were tested. Results show that all pair-wise combinations of those colors generated a clearly visible spreading effect, although of variable strength. Table 1 summarizes the rank orders as derived from the magnitude estimates. For example, a dark blue contour elicited the strongest effect when flanked by a yellow fringe, followed by red and green fringes. In general, it appeared that blue and red produced strong effects (similar to that achieved by the purple/orange combination of Fig. 1), whereas green and yellow yielded weaker effects.

2.6. Contrast

The Watercolor Effect was originally discovered in high-contrast (black outer line, light colored fringe) patterns (Pinna, 1987) where the color of the line with the weaker contrast to the ground produced a most striking effect. However, by changing the contrast of the outer contour relative to the colored fringe, we now know that color spreading is still present, albeit weaker, when the luminances of the two inducing lines are nearly identical. Under these conditions, color leaches outward about equally to either side. Moreover, there is a change in appearance from solid (pastel) to diaphanous (veil), as can be clearly seen on a gray background.

2.7. Additional observations

Color spreading occurs not only on a white or gray background, but also on *colored grounds*. There, the

Table 1
Strength of the Watercolor Effect for various color combinations

Contour	Color of flanking line (fringe)
Blue	Yellow, red, green
Green	Red, blue, yellow
Yellow	Blue, red, green
Red	Blue, green, yellow

[2] X/Y chromatic coordinates remain to be measured.

spreading color appears superimposed onto the color of the ground, but it does not mix. Even on a black ground, a haze of color is observed. Faint spreading can also be elicited by two achromatic inducing lines (e.g. a dark gray border flanked by a light gray fringe) on a white background and thus is not limited to the color domain. Although, under normal conditions, color spreading on a given area is uniform, two colors can be shown to spread simultaneously. For example, when in one of the lobes shown in Fig. 1, the top half of the inner edge is lined with one color and the bottom half by another, each color spreads about halfway onto the enclosed surface area.

Color spreading is strongest when viewed at *medium illumination*. Under a bright sun, the effect becomes weaker. *Blurring* the stimulus in a computer generated image or optically (by holding a -2.5 diopter lens in front of the eye) also reduces the effect. Spatial contiguity of the two inducing lines is important. When a *white gap* (empty zone) is introduced in between the outer border and the inner edge, color spreading is weakened and ultimately disappears.[3] For example, with a gap size of 5.7 arcmin, magnitude estimation fell to a value of 3.9, suggesting a diminishing interaction.

[3] The term 'inner' refers to the inducing line that spreads its color thereby producing a surface (the figure), whereas the term 'outer' refers to the line that induces less or no color spreading (the ground). The distinction between inner and outer lines no longer applies, when both lines are equiluminant and spread their color equally.

However, when *dotted lines*, instead of continuous inducing lines, are used, watercolor persists (Fig. 2). At short range (equivalent to a diameter of 14.5 arcmin), chains of paired dots even appear to produce stronger spreading than lines, although in absolute terms, continuous lines (6 arcmin wide) elicit superior effects. Indeed, the overall strength produced by chains of dots depends on how densely they are populated.

2.8. Dichoptic viewing

Color spreading is present not only in monoptic patterns, but also on stimuli presented in dichoptic view. When two differently colored borders were viewed dichoptically, one with each eye, the Watercolor Effect continued to be perceived. Furthermore, color spreading also persisted when the inner and outer borders were placed in perceptually different depth planes. Stereoscopic depth was produced by introducing different amounts of crossed and uncrossed disparity between the two inducing lines. This caused the inner line to appear in a depth plane nearer or farther than that of the outer line. The figures used were two ragged squares, placed inside each other. The larger square was 9.1 deg on the side, the smaller square 4.6 deg, and the observation distance was 25 cm. Eleven disparities each for far and near ranging from 0 to 20 arcmin in steps of 2 arcmin were used. Three observers (including author BP) capable of free-fusing stimuli were asked whether watercolor spreading was present in the fused stimulus.

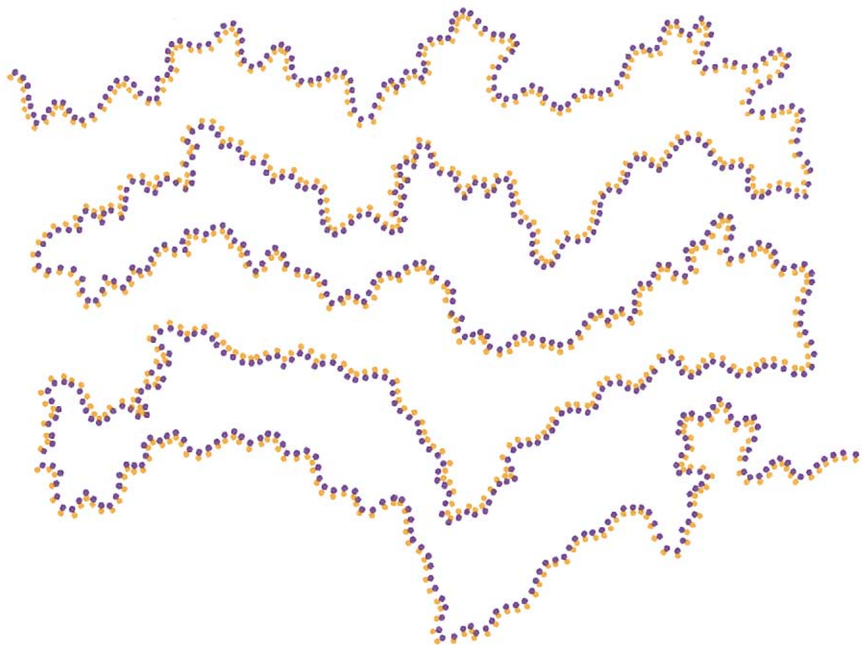


Fig. 2. Appropriately spaced pairs of purple and orange dots suffice to produce the Watercolor Effect.

Results show that for all disparities, crossed and uncrossed, watercolor spread uniformly across the enclosed area, thereby producing a colored surface that appeared to lie above (elevated) or behind (recessed) the ground. In these observations, watercolor spreading did not appear to become noticeably weaker with increasing disparity. Furthermore, there was no noticeable difference in strength or appearance of the watercolor between crossed and uncrossed conditions.

2.9. Gestalt effects

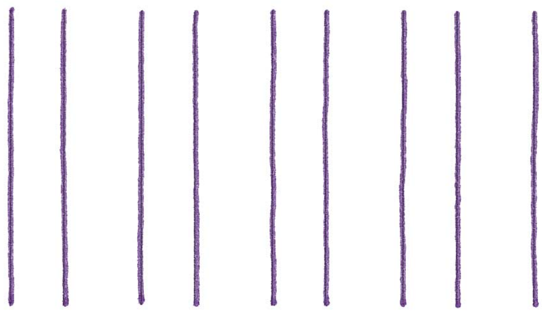
In addition to these findings, we noted a strong structural influence of the Watercolor Effect on *figure–ground* organization. This is demonstrated in Fig. 3. Here, the purple lines group according to the Gestalt factor of proximity (Fig. 3a). However, when orange fringes are added to the inner edges of the wide interspaces (Fig. 3b), perceptual grouping changes in favor of the water-colored surface, although the distance between grouped pair members is now larger than for non-grouped pair members.

In order to measure the influence of the Watercolor Effect on *proximity*, a stimulus pattern consisting of nine vertical purple lines with variable spacing and 6.3 deg in length was used. For a given stimulus pattern, the width of every other interspace was decreased (in consecutive steps of 0.57 deg), while keeping the interspaces in between constant. In this way, we obtained 13 stimulus patterns with interspace ratios ranging from 1:1 to 1:0.23 deg. There were three conditions: (i) pairs of purple lines whose inner edges were lined with orange fringes alternating with pairs of purple lines having no such fringes; (ii) the same patterns consisting of purple lines only, i.e. no orange fringes; (iii) the same patterns (as in the previous condition) consisting of orange lines only. Ten new subjects were tested in each condition, once for each stimulus pattern. Their task was to specify which of two interspaces, narrow or wide, appeared as figure and which as ground. In the first condition, results did not differ with stimulus spacing as 'figure' status was always assigned to the columns defined by watercolor spreading, irrespective of width ($F_{12,117} = 0.786$, $P < 0.6635$). In the two control conditions consisting of one inducing line only, the strength of figure–ground organization differed significantly with different interspace ratios (purple: $F_{12,117} = 6.437$, $P < 0.0001$; orange: $F_{12,117} = 6.35$, $P < 0.0001$). The smaller the distance between paired lines, the higher the likelihood that they were perceived as grouped. Thus, color spreading in condition (i) wins over proximity (conditions ii and iii). Furthermore, watercolor spreading also wins over *closure* as Fig. 4 illustrates. Here, the surrounding frame assumes the role of the figure, whereas the small rectangular fields appear as windows affording a view of the ground. Figure-ground organization reverses, when the orange fringe is absent.

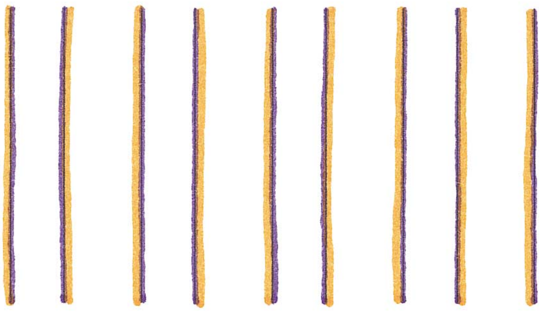
Table 2 summarizes the results on the watercolor effect.

3. Discussion

The Watercolor Effect described here is a striking example of a surface color (Katz, 1911) induced by a thin colored edge. It cannot be explained by Bezold or Helson-type assimilation (Helson, 1963; Jameson & Hurvich, 1975; Fach & Sharpe, 1986), as the assimilated area is much larger, and the inducing lines are thinner and further away from much of the induced color. In addition, there is a strong structural component, segregating the colored surface (the 'figure') from the ground. The Watercolor Effect is also different from other kinds of assimilation such as neon color spreading (van Tuijl, 1975; Bressan, Mingolla, Spillmann, & Watanabe, 1997). Neon color is transparent, extends over relatively short distances (Redies & Spillmann, 1981), and requires line ends (terminators) for inducing stimuli, although some spreading ('neon flanks') may also be perceived *along* the inducing lines (Redies et al., 1984).



(a)



(b)

Fig. 3. Spreading color serves to enhance figure-ground organization and promote grouping. In this example, the purple lines group according to the Gestalt factor of proximity (a), but group according to watercolor spreading if colored fringes are added to the inner edges (b). As a consequence, one perceives wide orangish columns (figures) separated by narrow white columns (ground).

The observation that an inducing line of only 6 arcmin is optimal for eliciting long-range color assimilation warrants the question for the mechanisms subserving the Watercolor Effect. The finding that chains of colored dots, instead of continuous lines, are sufficient for producing watercolor spreading implies a two-stage mechanism whereby color spreading starts locally, before it spreads globally. The first stage probably involves a high-spatial frequency mechanism that becomes disabled by blurring (as we have observed). This may be followed by a low-spatial-frequency mechanism, enabling large-scale, unbarriered color spreading onto the adjoining surface. (After low-pass filtering, dotted lines would be comparable to continuous lines.) The observation that the uniform spread of color is perceived in dichoptically presented stimuli further suggests a brain site at or beyond the level responsible for the perception of stereo-depth. Significantly, both local and global processing rely on spatial contiguity. When a sufficiently wide intervening zone is introduced separating the outer contour from the inner fringe, the Watercolor Effect is reduced to about half strength. Still, there remains some interaction between the colored inducing lines despite the gap.

Short-range and long-range interactions as the basis for color and brightness perception on extended surfaces have been discussed as early as 1960 by von Békésy (von Békésy, 1960), who distinguished between border (Mach) and area (Hering) contrast. This distinction finds an analogy in Broerse et al.'s (1999) recent conjecture that there are two qualitatively different effects, edge colors (fringes) and spread colors (surface colors). Below, we discuss the results of psychophysical, computational, and neurophysiological approaches to provide a basis for a better understanding of local boundary diffusion as a prerequisite for global surface spreading (i.e. Watercolor Effect).

Table 2
Main features of the Watercolor Effect (WCE)

Spatial limit of watercolor spreading about 45 deg
Uniform coloration complete at exposure duration of 100 ms
Optimal inducing line thickness approx. 6 arcmin
WCE stronger with winding (optimal 1.23 cpd) lines, but also present with straight inducing lines
Many-color combinations induce WCE, but blue and red are superior to green and yellow
Contrasting inducing lines best for WCE, but watercolor still present at near-equiluminance
WCE also on colored, gray and black grounds
Two colors from opposite edges spread halfway
WCE strongest under medium illumination, diminishes under high illumination
Blurring weakens and eventually abolishes WCE
White intervening zone (gap) weakens WCE
WCE also present with chains of paired dots
WCE seen also with dichoptic presentation
WCE present in stereoscopic viewing
WCE enhances figure/ground segregation
WCE promotes grouping between distant elements

Psychophysical studies have shown that chromatic sensitivity, at least over a small span of visual space (< 1 deg), is enhanced by luminance borders (Boynton, Hayhoe, & MacLeod, 1977; Cole, Stromeyer, & Kronauer, 1990) and pedestals (Switkes, Bradley, & DeValois, 1988). These results suggest a threshold mechanism by which a luminance edge (including a stereoscopically

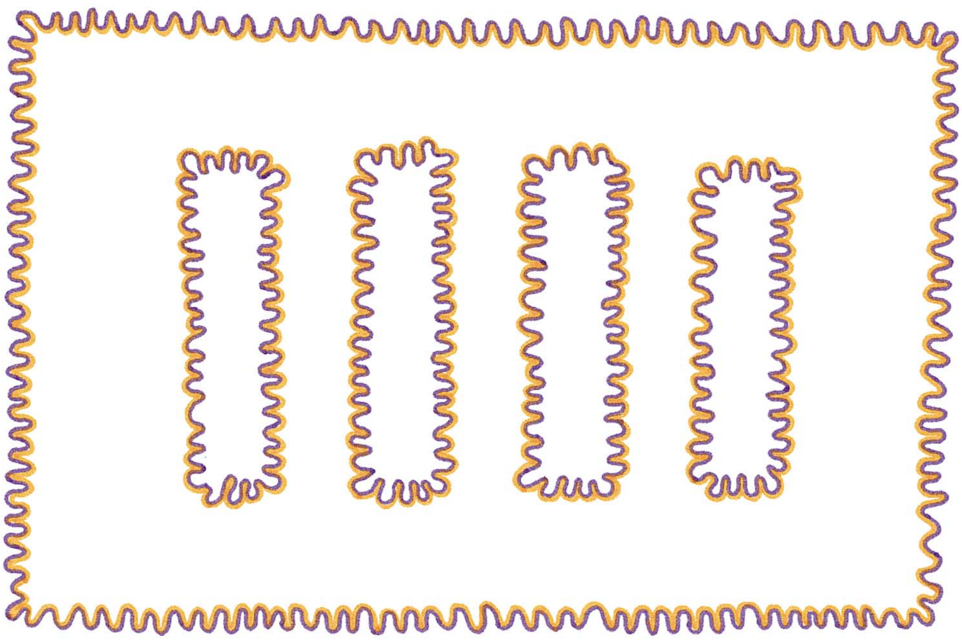


Fig. 4. Watercolor spreading wins over the Gestalt factor of closure.

defined edge) enclosing a chromatic patch should enhance sensitivity to color on the inside while containing color spreading to the outside (Montag, 1997; Gowdy, Stromeyer, & Kronauer, 1999). As the Watercolor Effect reported here is strongest with a darker outside border (i.e. a luminance change), it may benefit from the above threshold mechanism. However, such a mechanism does not easily explain why, under our conditions, suprathreshold color spreading persists over large angular subtenses, even when the two inducing lines have close-to-equal luminances. Further experiments using a shorter (than 100 ms) exposure duration may clarify whether there is any spatial propagation emanating from the edge (Paradiso & Nakayama, 1991).

How about the interaction between the inner and outer inducing lines (fringe and contour)? A weakening of the boundary as a prerequisite for the outflow of color is at the core of the neuro-computational model of color and form perception by Grossberg and Mingolla (1985). This model distinguishes between two processing modes, the Boundary Contour System for generating perceptual boundaries and the Feature Contour System for triggering the filling-in process by which color (and brightness) spreads until it is stopped by boundary contours. Whereas the original model (Grossberg & Mingolla, 1985) restricted spreading to lines abutting each other at their terminals (e.g. neon color in the Ehrenstein figure), newer versions of the model also accommodate color spreading from lines *flanking* each other (Grossberg, personal communication).

There may also be analogies between the Watercolor Effect and the spreading of neural activity and brightness in the Craik–O'Brien–Cornsweet illusion (for the latter, see Grossberg & Todorovic, 1988; Gilbert, 1992; Spillmann & Werner, 1996; Hung, Ramsden, & Roe, 1998). Note, however, that this illusion is typically elicited by a saw-tooth or an edge similar to a saw-tooth (Ratliff & Sirovich, 1978; Todorovic, 1983) and is stronger for achromatic than for equiluminant chromatic stimuli (Wachtler & Wehrhahn, 1997), whereas the Watercolor Effect is more pronounced with color.

In neurophysiological terms, assimilative color spreading — as reported here — could be initiated by lateral inhibition between differentially activated luminance edge cells. For example, cells with receptive fields aligned along the purple/orange edge transition (Fig. 1) would be strongly activated and so could inhibit the competing, but lower, response of neighboring cells aligned along the orange/white transition. Consequently, the orange color would then be locally released ('diffused') to spread beyond that weakened edge. The purple/white transition, being of a higher luminance contrast, should resist inhibition better and thus would be expected to release little purple, as is seen by the white adjoining area. This assumption might explain why colored lines of similar luminance produce a weaker, bilateral effect.

As an alternative, color-oriented cells in area V1 showing a correlated activity with non-oriented neurons in area V2 (Roe & Ts'o, 1999) may contribute to large-scale color and brightness induction from object boundaries. Such correlated activities are conveyed to higher extrastriate areas that are involved in color and form (and possibly surface) processing. The larger receptive fields of these cells may thus be candidates for mediating the perceived filling-in of color in the Watercolor Effect. Note, however, that the Watercolor Effect is stronger for chromatic than for achromatic stimuli and that all tested combinations of colored lines can generate the illusion, although at different strengths. Further studies may be needed to explain why wavy inducing lines are superior to straight lines and why bright illumination is detrimental to the effect.

4. Conclusion

The Watercolor Effect, described here, may serve to enhance figure–ground segregation by imparting surface color onto the enclosed area (Fig. 1) and to promote grouping between distant stimulus elements (Fig. 3). In either case, the coloration is uniform across, and there is no thinning of color towards the middle of a segregated surface, even if this surface is partially open (as in Fig. 1). This may suggest a unified change in appearance by some high-level descriptor that generalizes the flanking color at the edge across the entire enclosed area. However, the observation that two watercolors may be simultaneously present, each in its own half, when a given stimulus lobe is lined with different colors, speaks in favor of a propagation from the edge onto the enclosed area. The Watercolor Effect may thus be another example of a color filling-in phenomenon (Friedman, Zhou, & von der Heydt, 1999), although it is large-scale, seemingly instantaneous, and does not require strict fixation to stabilize the image on the retina.

The strong *figure–ground segregation* emerging from watercolor spreading suggests that a neural mechanism based on color leaching outward in the interest of surface representation and border belongingness (i.e. the boundary defines the figure, not the ground), may be the most parsimonious way of looking at this effect. Its presence with dichoptic viewing points toward a cortical origin. The additional feature of *grouping by color spreading* reinforces the role of the Watercolor Effect as a novel and powerful Gestalt factor, superior to proximity. These figure–ground qualities further distinguish this effect from any of the other assimilation effects mentioned above (Helson, 1963; Redies & Spillmann, 1981) and establish it as one of a new class of color-spreading phenomena.

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