Physiological correlates of watercolor effect

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The watercolor effect is a visual illusion that manifests itself as a combination of long-range color spreading and figure–ground organization. The current study uses behavioral and physiological measures to study the watercolor effect. We utilize a novel technique of measuring the cortical response of the illusion using the visual evoked potential (VEP). To this end, three experiments were done to investigate the contributions of luminance and hue to the magnitude of the illusion. Results of both VEP and behavior indicate a marked decrease in the −S (yellow) direction in illusion magnitude compared to the +S (blue) illusion, even though these colors were previously matched for perceptual salience. © 2013 Optical Society of America

1. INTRODUCTION

In the context of the visual system, spatial contrast can be defined as local differences in luminance or chromaticity. The visual system utilizes contrast information as the major source of information to segment the visual scene and provide for our vision. Because much information about absolute luminance and chromaticity is lost, the resultant percept of a particular region in visual space depends greatly upon context. For example, while working for a fabric-dyeing manufacturer, Chevreul [1] noted his observations in response to complaints about the “want of vigour” of black cloth. He concluded that it wasn’t the dye itself that made the black look odd but the surrounding colors and coined this phenomenon “simultaneous contrast of colors.” In particular, lighter colors made the black appear darker, and darker colors made the black appear lighter. A seemingly opposite effect known as assimilation was described in 1876 by Von Bezold [2] who observed that thin black and white arabesque patterns that were surrounded by different colors made the surrounding hues darker and lighter, respectively. In addition to these brightness effects, the percept of color also displays assimilation and simultaneous contrast effects.

The probability of the occurrence of assimilation versus simultaneous contrast depends upon the spatial parameters. Helson [3] found that by adjusting the spatial frequency of achromatic bars, the brightness induction of the bars switched from assimilation to contrast when transitioning from high to low spatial frequencies. The transition point seems to take place at around four cycles per degree of visual angle. This same switch has been shown to occur with chromatic gratings as well [4, 5]. When gray bars are inserted into a black and white square wave grating, they will appear lighter or darker when placed on top of the white or black lines, respectively. This is known as White’s effect [6]. White’s effect in its achromatic form poses a question as to whether the perceived lightness of the gray bars is caused by contrast from the embedding bars or assimilation by the flanking bars. By changing the black and white bars to noncomplementary colored bars, Anstis [7] showed that both contrast and assimilation contributed to the perceived hue of the gray bars. This implies that contrast and assimilation can simultaneously contribute to the perception of a surface color. In a recent review article about color in the cortex, Shapley and Hawken state that color assimilation may be due to activity of single opponent cells, while color contrast may depend on double opponent cells [8].

Although assimilation has typically been shown to occur over short distances in the presence of high spatial frequencies, there also are examples of long-range assimilation such as neon color spreading [9–11] and the watercolor effect [12, 13] wherein induced colors spread over a relatively large area. The watercolor effect results from the juxtaposition of two lines differing in color and/or luminance, whereas neon color spreading is the apparent continuation of colored lines [14]. These illusions differ in that the watercolor illusion appears “opaque,” while the neon color spreading appears more “transparent.”

In the watercolor effect, areas bordered by juxtaposed lines adopt an illusory tint similar in hue to the inducing line. The line that best induces the effect is the line that contrasts least with the background. Pinna has coined this observation the “asymmetric luminance contrast principle.” This concept was known centuries ago by cartographers who used a similar principle to delineate countries from each other as well as water from land [15, 16]. The luminance contrast of contours has been shown to be a stronger indicator of figure–ground delineation than the classic Gestalt grouping principles [17]. A study done by von der Heydt and Pierson [18] showed that the illusory color and figure–ground aspects of the watercolor effect may be caused by independent neural mechanisms. A neural model accounting for these phenomena is given by Pinna and Grossberg in which cooperative and competitive
boundary completion processes would allow an illusory surface color to spread. They propose layer 2/3 of cortical area V2 as a possible neural substrate.

Pinna et al. [13] showed that the magnitude of the watercolor effect can be manipulated as a function of distance of color spreading, exposure duration, line thickness, waviness of lines, inducing color, and luminance contrast of the lines. These pioneering studies were done with colored markers on paper using the method of magnitude estimation. Devinck et al. [19] performed a study focusing specifically on quantifying the effects of chromaticity and luminance on the watercolor effect. This study used color-matching and hue-cancellation techniques in order to measure the magnitude of the watercolor effect. The amount of color needed to simulate (matching) or null (hue cancellation) the illusion was divided by the vector length of color (from the white point) used to produce the inducing contour, which gives a percentage of illusion strength. In a follow-up study, Devinck et al. [20] looked at hue contrast of the two inducing contours, saturation (or colorimetric purity) of the contours, and isoluminant S and L-M cone stimuli.

An achromatic version of the watercolor illusion was studied by Cao et al. [21]. They were able to measure the effect by comparing it to darker adjacent control regions that didn’t have the illusion. By holding the inducing line constant, they were able to manipulate the magnitude of the illusion by adjusting the luminance of the outer contour. By adjusting the luminance level of the outer line well above and below the background and inner line, they measured the illusion when the outer line was darker, lighter, and in between the background and inner line.

Devinck et al. [22] studied the watercolor effect as a function of inducing width and found that at more narrow inducing areas, the watercolor effect is stronger and also more affected by chromatic aberration, whereas longer-range spreading was not affected by chromatic aberration and is presumably a neural phenomenon. Other non-neural or prerceptual factors such as light scatter have been suggested as possible causes of assimilation [5]. However, others have shown that chromatic assimilation cannot be explained by these factors alone and must involve some neural computations [23].

The first objective of the present study was to measure the strength of the watercolor illusion as a function of brightness and hue of the inducing lines with the inner line always being chromatic and the outer line achromatic. A second goal was to utilize the chromatic visual evoked potential (VEP) to objectively quantify the strength of the effect and to compare the cortical responses to psychophysical measurements. Three experiments were completed using VEP and psychophysics. The first experiment quantified the magnitude of the illusion as a function of the luminance of the outer contour, and the second experiment as a function of the luminance of the inner contour. Optimal luminance values of the first two experiments were used in the third experiment, which compared the illusion magnitude as a function of chromaticity for hues that were matched in perceptual salience.

2. METHODS

A. Participants
College students from the University of Nevada, Reno, participated in this experiment. Each observer provided informed consent to participate. Procedures were approved by the University’s Office of Human Research Protection and conformed to the tenets of the Declaration of Helsinki. Prior to the experiment, normal color vision of each observer was verified using the Cambridge Colour Test and Ishihara Plate Test.

B. Apparatus
Stimuli were displayed on a CRT monitor (Sony Multiscan 20 SE 2) and were generated with a VSG 2/3 graphics card (Cambridge) in a PC running custom software. The monitor was calibrated using a PR 650 spectrophotometer (Photo Research) and an optiCAL photometer (Cambridge). The experiment was performed in a dark room, and participants viewed the monitor from a distance of 114 cm. VEPs were recorded using Grass gold electrodes and bioamplifiers. Signals were filtered (low-pass = 100 Hz; high-pass = 1 Hz), digitized with a data-acquisition device (National Instruments), and stored on a PC for off-line analysis.

C. Stimuli
Stimuli comprised a collection of thin aligned arcs to appear as a series of columns (see Fig. 1). Each arc was 4.5 arc min wide (9 arc min arranged in pairs of two), and each column was roughly 0.66 deg wide by 6.7 deg long and separated from each other by about 0.37 deg. The inducing (experimental) stimulus consisted of all chromatic arced lines on the inside of the columns and all achromatic arcs on the outside. The noninducing (control) condition comprised braided chromatic and achromatic arcs, which did not produce the illusion [24]. All stimuli were presented on a gray background, which was slightly adjusted in luminance for each experiment.

For the behavioral psychophysics, the experimental and control conditions were presented simultaneously with each pattern approximately 0.7 deg to the left and right of a median line (see Fig. 1). These relative positions were counterbalanced. For VEP recording, only one pattern (centrally fixated) was shown at a time, and the stimulus alternated between the inducing pattern and the control pattern.

3. PROCEDURE

A. Psychophysics
Devinck and Knoblauch [24] introduced a method to measure the watercolor illusion using maximum likelihood difference scaling in which they presented participants a triad of illusions. The observer picked which of the bottom two was more similar to the one on top. This method, which allowed for a direct comparison of the strength of the illusion with different luminance ratios, was reported as being easy for participants and produced less variability than other methods. However, one important goal of this study was to compare the strength of the watercolor illusion across hues (Experiment 3). Consequently, we were unable to employ the technique of Devinck and Knoblauch since the similarity judgment task was complicated by hue differences in this context. We therefore used contrast-matched colors [25,26] as described in Experiment 3, and a two-alternative forced-choice paired comparison test wherein we compared an inducing pattern to a noninducing pattern (Fig. 1).

Participants were told that their task was to judge which of the two patterns appeared more colored on the inside of the columns. Participants were instructed to fixate along the median line. The inner areas of the control columns were
tinted with variable amounts of color to simulate the illusion. Twelve chromaticities along a vector in color space from the gray background to the inducing contour were used to fill in the control columns. Each image was presented in random order and appeared on the screen for 250 ms and then disappeared. During this blank-screen period, a button press from the participant would advance them to the next trial. The stimuli were presented brieﬂy to more closely match the temporal conditions used for the VEP.

B. Visual Evoked Potentials

VEPs were differentially recorded with an active electrode at Oz, a reference electrode at Pz, and a ground electrode at Fz, according to the international 10/20 system [27] and ISCEV standards [28]. Electrode impedances were kept under 10 kΩ and measured at 30 Hz. Participants were instructed to remain still and fixate on a small cross in the center of the middle column. Participants binocularly viewed patterns exchanging at a rate of four times per second (250 ms per pattern). Prior research has shown that presenting stimuli at these rates produces a large chromatic VEP response [29]. The series was viewed for 1 min for a total of 240 exchanges.

We used two conditions termed “experimental” and “control.” In the experimental condition, the inducing pattern and the noninducing pattern were exchanged. In the control condition, mirror images of the noninducing pattern were exchanged. In the experimental condition, the percept of the illusion occurs every other presentation at a rate of 2 Hz, whereas more general pattern, motion, and local luminance/chromaticity changes occur at a rate of 4 Hz. Pilot studies showed a marked increase in the 2 Hz component of the experimental condition compared to the control condition while controlling for size, luminance, and chromaticity of the stimulus.

We reasoned that the magnitude of the 2 Hz component of the response in the experimental condition could be used as an indicator of the strength of the illusion. Any difference between the responses to each pattern should be reﬂected in the 2 Hz signal. The 4 Hz component represents the transient pattern response to each exchange. The control condition was used to check if there was any contribution to the 2 Hz component from sources other than the illusory appearance of color. In the control condition wherein two mirror image controls were exchanged, the 2 Hz component should be negligible, but the 4 Hz component should remain prominent and similar to the 4 Hz responses in the experimental condition.

4. EXPERIMENT 1: LUMINANCE OF OUTER CONTOUR

Prior behavioral studies have shown that manipulating the luminance ratio of the inner and outer contours can affect the illusion strength [13,19,21]. Our ﬁrst experiment sought to investigate if there was any consistency in the way the illusion strength could be modulated as a function of outer contour luminance. We tested seven participants in the psychophysical portion of Experiment 1. In this experiment, the luminance of an achromatic outer contour was parameterized. The background was held at a ﬁxed chromaticity (CIE x = 0.317, y = 0.337) and luminance (27 cd/m²). The inner contour was orange (CIE x = 0.44, y = 0.46; luminance = 27 cd/m²). The outer line was presented at six luminance values: 1, 9, 18, 27, 36, and 45 cd/m². The chromaticity of the inner control columns used 12 increments of saturation of the orange. Each participant completed three blocks of the task. Each luminance level tested consisted of 12 sublevels of color in the control equally spaced from 0 to approximately 14% in MacLeod–Boynton–Derrington–Krauskopf–Lennie (MBDKL) color space [30,31]. These 12 chromatic steps were presented at each of the six luminance levels, once on the right and left, for a total of 432 trials per subject (3 × 12 × 6 × 2).

A. Experiment 1 Results: Psychophysics

Matches for individual observers were determined by ﬁtting a Weibull function [32] to the data for each luminance level after pooling data from both position conditions. The saturation of the added color that produced 50% performance was taken as the magnitude of the illusion for each luminance value. The averaged data are plotted in Fig. 2 as a percentage of inducing contours in MBDKL space, which represents the data as a function of cone contrast. The results show that an increment (right side of zero, outer line more bright) and decrement (left side of zero, outer line more dark) in luminance of the outer contour produced a measurable illusion. Moreover equal luminance increments and decrements produced approximately equal illusion magnitudes. There is an expected, pronounced drop in the magnitude of the illusion when the luminance of the outer contour is equal to the background (i.e., the achromatic outer contour is absent).

B. Experiment 1 Results: VEP

The VEP signals were analyzed in the frequency domain using a fast Fourier transform (FFT). The 2 and 4 Hz frequencies (fundamental and second harmonic) were tested using the T-circ statistic [33]. Five out of the seven observers who participated in the psychophysics also participated in the VEP portion of Experiment 1. The data for one subject were omitted from analysis due to insigniﬁcant response amplitudes. Data were collected for 12 trials: one control and one experimental trial for each of the six luminance levels. The 2 and 4 Hz components are plotted as a function of contrast [Figs. 3(a) and 3(b), respectively] of the outer contour with the background. Results show a marked difference between
the experimental and control conditions as a function of contrast for the 2 Hz component, with the experimental condition being larger in amplitude across all conditions. Although there is a pronounced dip at the point of the outer contour disappearing (0 point), the 2 Hz amplitude for the experimental condition appears to peak not at the highest contrast (as in the psychophysics), but rather at medium contrast levels on both sides of the 0 point.

All participants showed a minimum in the 4 Hz response at the 0 contrast point, as expected. At this point, the only 4 Hz component in the stimulus is the abrupt motion of orange arcs that are nominally isoluminant with the background, making it rather difficult to detect the exchange of the stimulus. The 4 Hz amplitudes for the experimental and control conditions do not differ as much as the 2 Hz amplitudes and the control condition produced marginally larger 4 Hz amplitudes.

C. Experiment 1.2: Additional Check

If the 2 Hz response in the experimental condition of the VEP experiment were due to the percept of color from the watercolor illusion, instead of other factors, then we should be able to produce similar results by introducing physical chromaticity into one of the two control patterns. An experiment was completed to test this hypothesis by filling the interior column areas of one of the control patterns with a chromaticity that was a psychophysical match of the illusion (derived from the psychometric functions of Experiment 1).

Three observers participated in this experiment, and the averaged amplitudes after the FFT are shown in Fig. 4. Again, we see a large difference between experimental and control conditions at 2 Hz and also a difference between the filled control and control conditions. Interestingly, the filled control did not produce a 2 Hz response as large as the experimental condition. One possible explanation of these results is that the illusion not only produces color in the insides of the columns but also complementary colors in the exterior region (noted anecdotally), while our control was only filled in the internal areas of the columns. Another possible contribution to the experimental 2 Hz signal could be due to the luminance edges being aligned and misaligned at the rate of 2 Hz, while in the control they were always misaligned. Nonetheless, these results support our interpretation that the large 2 Hz response seen in the experimental condition is due to the induction of color.

5. EXPERIMENT 2: LUMINANCE OF INNER CONTOUR

The luminance of the inducing contour also is an important factor in producing the watercolor effect [19,24]. The focus of Experiment 2 was to take one of the optimal outer contour luminance levels from Experiment 1 and hold it constant while manipulating the luminance of the inner contour. Recall that in the first experiment, the luminance of the inner counter was held isoluminant to the background. Eleven people participated in the psychophysics and VEP portions of Experiment 2. In this experiment, the outer contour was held at 9 cd/m² (which, from the results of Experiment 1, produced a psychophysically and physiologically measurable illusion), and the background was set to 23 cd/m². The luminance of the inner orange line was varied over six different levels: 9, 14, 18, 23, 27, and 36 cd/m². Since the color-inducing inner lines varied in luminance, the color vector used for the matching fill colors included the corresponding luminance differences. The remaining conditions for psychophysics and VEPs were similar to those of Experiment 1.

A. Experiment 2 Results: Psychophysics

Out of the 11 people tested, two participants failed to produce reasonable psychometric functions, and their data were omitted (one participant always picked the illusion condition;

![Graph](image1)

Fig. 2. Effect of outer contour luminance on the magnitude of the watercolor illusion. Error bars indicate ±1 standard error of the mean. X axis represents Weber contrast of outer contour to background. Y axis represents percentage of inducing contour needed to match illusion in MBDKL color space.

![Graph](image2)

Fig. 3. Averaged VEP amplitudes (extracted from FFT) for the 2 and 4 Hz components as a function of contrast between the background and the outer contour. X axis represents Weber contrast of outer contour to background. Error bars indicate ± 1 SEM. The units of Fourier amplitude approximate microvolts by multiplying by a factor of 0.04.
another always picked the control condition). The results of Experiment 2 reveal small responses at the extremes wherein the luminance of the inner and outer contours are equal (−0.61 contrast, see Fig. 5) and when the inner contour is much brighter. The magnitude of the illusion appears to be maximal around the point where the inner contour and the background luminance are equal (0).

B. Experiment 2 Results: Physiology
Two out of the 11 subjects in Experiment 2 didn’t produce any statistically significant 2 Hz components for any of the VEP conditions according to the T-circ statistic (p > 0.05), and their data were omitted from further analysis. Figures 6(a) and 6(b) show the results for the 2 and 4 Hz amplitudes, respectively. As in Experiment 1, the 2 Hz difference between the two conditions is larger than the 4 Hz condition. The VEP results largely mimic those seen in the psychophysics. The maximum amplitude differences between the experimental and control 2 Hz signal occurs around isoluminance and decreases when the contrasts are most extreme. In agreement with the psychophysics, the point at which the inner and outer contours are matched in luminance (and in this case both darker than the background) produces the least response.

6. EXPERIMENT 3: COLOR OF INNER CONTOUR
A. Equating the Saturation of Different Hues by Contrast Matching
In order to compare the strength of the illusion across different colors in a meaningful way, one must equate the intensity of the colors on some basis. Since chromatic contrast is ill-defined for different directions in color space, we chose to equate the strength of the inducing colors on the basis of perceptual salience using supra-threshold contrast matching [25,26]. Switkes and Crognaite showed that this technique agrees well with threshold psychophysical scaling but is more precise for stimuli that are far above threshold.

Equation of the color salience was accomplished by comparing the visibility of two different columns from the control pattern as described above. The test columns comprised 18 cd/m² chromatic arcs braided with achromatic arcs of 10 cd/m² (which was the luminance of the outer contour used in Experiment 3), and the reference columns had the same achromatic arcs (10 cd/m²) braided with incremented achromatic arcs of 21 cd/m². The background CIE chromaticity coordinates were (0.31, 0.317) with a luminance value of 18 cd/m². Thus each pattern containing colored arcs was equated to the same achromatic pattern (dark gray/colored columns compared to dark gray/light gray columns). For these determinations, test colors fell along the +S, −S, +LM, and −LM opponent axes of MBDKL color space [30,31], as well as four points that fell along two intermediate axes. Using the method of adjustment, observers set the saturation of the chromatic portion of the test columns until they appeared to be as equally visible as the achromatic columns. This procedure was repeated multiple times for each of the eight hues and averaged for individual observers. These individual matched hues were then employed for psychophysical and VEP testing in Experiment 3.

B. Experiment 3: Watercolor Hue
The purpose of this experiment was to compare the strength of the illusion across different chromaticities that were perceptually matched in visibility. The matching chromaticities defined the endpoints of test vectors for each individual and were used to calculate the different levels of the distance in color space of the control columns. These vectors extended from white toward one of the eight chromaticities. The CIE coordinates of the average chromatic vector endpoints are given in Table 1. Individual values differed slightly depending upon their individual contrast matches. This psychophysics experiment was similar to the previous experiments described, except it was a 2 × 8 × 12 design containing 192 trials per run, including each of the eight colors presented once on the left and once on the right with 12 steps of inner color in the control pitted against each colored illusion. Out of the 12 participants in this study, seven completed three runs, two completed two runs, and three completed one run of the psychophysics.

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Fig. 4. Averaged VEP amplitudes (2 and 4 Hz components) of experimental (illusion), filled control (control with tinted inner area), and control (no filled/illusory color).

Fig. 5. Averaged percentage of the inducing color match as a function of the luminance contrast of background and inner (chromatic) contour. X axis represents Weber contrast of inner contour to background. Error bars indicate ±1 SEM.
Three of the participants who completed three psychophysics runs also completed VEP recordings for experimental and control conditions for the corresponding hues.

C. Results Experiment 3: Psychophysics

An average plot of the watercolor illusion magnitude as a function of hue of inducing contour is shown in Fig. 7. The psychophysics data are averaged across 12 observers. The distance of each point from the origin represents the percentage of the inducing line vector that was matched to the illusion, and the angle of each point with respect to the origin represents different hues. Although individual differences existed between observers, one consistent observation is that the $-S$ (lime/yellow) direction required a smaller percentage of its inducing contour to make a match than the other chromaticities, especially the $.0135S$ (violet), which for most observers required the highest percentage.

D. Results Experiment 3: Physiology

The VEP results from Experiment 3 are shown in Fig. 8. These are averaged across the three observers. All experimental 2 Hz amplitudes were greater than 2 Hz control amplitudes. As in the first two experiments, the 4 Hz amplitudes do not differ significantly between the two conditions. The 2 Hz VEP

Table 1. CIE $x$ and $y$ Coordinates and Corresponding Color Angle of Supra-Threshold Contrast Colors Averaged across Observers

<table>
<thead>
<tr>
<th>MBDKL Angle</th>
<th>0</th>
<th>27</th>
<th>90</th>
<th>153</th>
<th>180</th>
<th>207</th>
<th>270</th>
<th>333</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIE $x$</td>
<td>0.34</td>
<td>0.29</td>
<td>0.29</td>
<td>0.27</td>
<td>0.28</td>
<td>0.32</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>CIE $y$</td>
<td>0.3</td>
<td>0.24</td>
<td>0.26</td>
<td>0.27</td>
<td>0.33</td>
<td>0.38</td>
<td>0.42</td>
<td>0.38</td>
</tr>
</tbody>
</table>

*Each observer used their own personal matches for the experiment.

Three of the participants who completed three psychophysics runs also completed VEP recordings for experimental and control conditions for the corresponding hues.

Fig. 6. Average VEP amplitudes of 2 Hz (left) and 4 Hz (right) components as a function of the luminance contrast of background and inner contour. X axis represents Weber contrast of inner contour to background. Error bars indicate ±1 SEM.

![Fig. 6](image)

![Fig. 7](image)

![Fig. 8](image)
and the psychophysics data are similar in character to each other, particularly with regard to the asymmetric nature of the $S$ axis responses.

7. DISCUSSION

This series of experiments quantified changes in the magnitude of the watercolor effect as a function of luminance contrast and chromaticity using psychophysics and the VEP. Overall the VEP recordings reflected the estimates from psychophysics. As predicted, the 4 Hz signal was not significantly different in the experimental and control conditions and is attributed to the transient pattern response at the exchange rate of the stimuli. The 2 Hz amplitude represents a response to the difference between the exchanged images and was larger in those experimental conditions where the illusion was present. The 2 Hz signal was taken to be the physiological correlate of the illusion magnitude when compared to psychophysical measures. While the 4 Hz response was much larger than the 2 Hz in the control condition, the experimental condition produced 2 and 4 Hz responses of similar amplitudes.

In Experiment 1, psychophysics revealed a v-shaped curve minimized when the outer contour became isoluminant (disappeared) with the background and seemed to top out at the extreme contrast levels. The 2 Hz VEP curve for this experiment produced more of an m shape, where the 2 Hz components of the extreme luminance levels actually decreased slightly over those obtained at intermediate contrast levels. Previous behavioral studies also have shown that the watercolor effect works best when the lines are set at intermediate contrasts with each other [13,21]. One possible reason that Experiment 1 of the current study might not have obtained an m-shaped psychophysics function may be because we did not allow for the manipulation of hue or luminance, but only adjusted saturation in the forced-choice paradigm. Thus the best-matching chromaticities may not have precisely matched the illusory percept.

Most previous studies on the watercolor effect have designed their stimuli with the outer contour being darker than the inner contour and the background. Devinck et al. [19] found that the magnitude of the illusion decreased when the outer contour became brighter than the inducing contour. Their study differed in that both of the contours were quite darker than the background, while in the present study, the inner contour luminance was equal to the background. Cao et al. [21] had the luminance of the outer contour span a range well above and below the background and inner contour (in their experiment the inner contour was darker than the background) and showed that an increment and decrement of the outer contour produces an illusion of decreased luminance.

In Experiment 2, the low point of the illusion occurred when the two contours were the same brightness and both dimmer than the background. This made the inner orange contour rather difficult to see. Increasing the brightness of the orange contour increased the magnitude of the illusion until the inducing contour was approximately equal (or slightly brighter) in brightness to the background. When the orange became noticeably brighter than the background, the illusion seemed to wane. In the psychophysical portion of this experiment, we manipulated luminance in conjunction with saturation of the inner chromaticity of the control columns, which may have contributed to the decrease in the illusion seen at high luminance levels. Some prior studies have found a steady increase in illusion magnitude as a function of luminance contrast of the inducing contour [19,24]. However, in these studies the illusion was not measured when the inducing contour was brighter than the background.

Experiment 3 showed that the watercolor effect is weaker for the $-S$ (yellowish) direction than for most other directions, notably $+S$. The $+S$ condition produced the strongest illusion by psychophysics and VEP. Pinna et al. [13], when measuring induced color using magnitude estimation, stated, “In general, it appeared that blue and red produced strong effects... whereas green and yellow yielded weaker effects.” Devinck et al. [19] found that “for all observers yellow spreading was the weakest effect.” Fach and Sharpe [4] also reported minimal assimilative spreading for yellow compared to other colors for their square-wave grating stimuli. It is notable that we obtained these same results despite equating the chromaticities for perceptual salience, essentially increasing the relative saturation of $-S$ to that of $+S$.

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