The effect of contrast intensity and polarity in the achromatic watercolor effect

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The watercolor effect (WCE) is a filling-in phenomenon in a region demarcated by two thin abutting lines. The perceived chromaticity of the region is similar to that of the interior line. We develop a series of achromatic WCE stimuli to induce lightness changes analogous to the induced chromaticity in the chromatic version of the WCE. We use a variation of the paired-comparison paradigm to quantify the induced lightness of the filled-in regions to regions with real luminance variations. The luminance of the inner line is fixed, while the luminance of the outer line varies across stimuli. Data from seven subjects (five naive) confirm that an achromatic WCE exists. Moreover, outer lines with both high and low luminances can generate a WCE with an inner line of a moderate luminance. All subjects show a single peak of the effect strength for both polarity conditions, which is never at the extreme luminance levels. Most subjects show an inverted U curve for effect strength as a function of the contrast of the outer lines against the background. Results suggest that the contrast difference between the outer line and the inner line affects the existence and the strength of the achromatic WCE in a nonlinear way.

Introduction

When a surface is surrounded by two thin abutting lines, it tends to be perceptually "filled-in" with the color of the interior line (Pinna, Brelstaff, & Spillmann, 2001). For example, a high-luminance region would usually appear white. When it is surrounded by a bright orange line that is further surrounded by an abutting dark purple line, the region will look orange with lower saturation than that of the orange line. The hue of the filling-in color is very similar to that of the interior line. Further, higher contrast between the two lines leads to a stronger WCE, while lower contrast between them weakens the effect (Devinck, Delahunt, Hardy, Spillmann, & Werner, 2005; Pinna et al., 2001). When the subjects have the freedom to manipulate both luminance and color to match the perception of the WCE, they do not need to change the luminance to make the match (Devinck et al., 2005).

Few studies have quantitatively measured the lightness illusion in an achromatic WCE (Takashima, 2008). Furthermore, if the achromatic WCE does exist, then can

we observe a contrast effect similar to that in the chromatic WCE, which is that the higher the contrast between the lines, the stronger the effect? If so, then can we use the achromatic WCE to measure this effect in a wide contrast range, including the situation when the two lines have an opposite contrast against the background, in which condition the WCE is rarely measured? One might expect a monotonic increase of the strength of the effect as the contrast between the lines increases (Devinck et al., 2005; Pinna et al., 2001). One may also expect a weaker effect when the two lines have an opposite contrast polarity against the background than that when the two lines have the same contrast. According to the observation of the figure–ground effect in the chromatic WCE, the effect gets weaker when the background luminance is between the luminance levels of the two lines, compared to the standard configuration in which the two lines have the same luminance contrast polarity against the background (Pinna & Reeves, 2006, Figures 7 and 8).

We developed a configuration of the achromatic WCE and an experimental paradigm to appropriately address these questions.

Methods and materials

Because pilot experiments with a matching task yielded results that did not consistently capture the perception of an achromatic WCE, we created a procedure as follows, which is explained in detail in the Procedure section. In each trial, the subject was asked to choose one of the two areas within an annulus stimulus as the darker area compared to the other. One of the areas was enclosed by lines that induced an illusory lightness decrement, while the other was not. However, the luminance of the former area was the same as the background luminance, while the luminance of the latter area was lower than the background luminance. In other words, we wanted the subjects to compare the illusory lightness reduction induced by the achromatic WCE with the lightness reduction as the result of the "direct" decrease of "real" luminance. We use the word "darkness" to refer to a perceived phenomenon of lightness decrement for the subjects as well. The details are given as follows.

Apparatus

Stimuli were displayed on a 24″ EIZO ColorEdge CG241W LCD monitor (width: 52 cm; height: 32 cm; resolution: 1600 × 1050) connected to a PC running Microsoft Windows XP. Stimuli were generated with Matlab 7.0.0 (R14) and saved as bitmap files. The experiment was run under Matlab 7.0.0 with Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The monitor was calibrated with the Spyder3 Utility and confirmed with a Photo Research PR-650 spectrophotometer. A linearized gamma lookup table was generated. Subjects sat comfortably at a distance of approximately 56 cm, with their heads stabilized by a chin rest.

Stimuli

The pattern of the stimuli is shown in Figures 1A and 1B. Each stimulus contains two enclosed areas (areas a and c in Figures 1A and 1B) along an annulus ring on a uniform
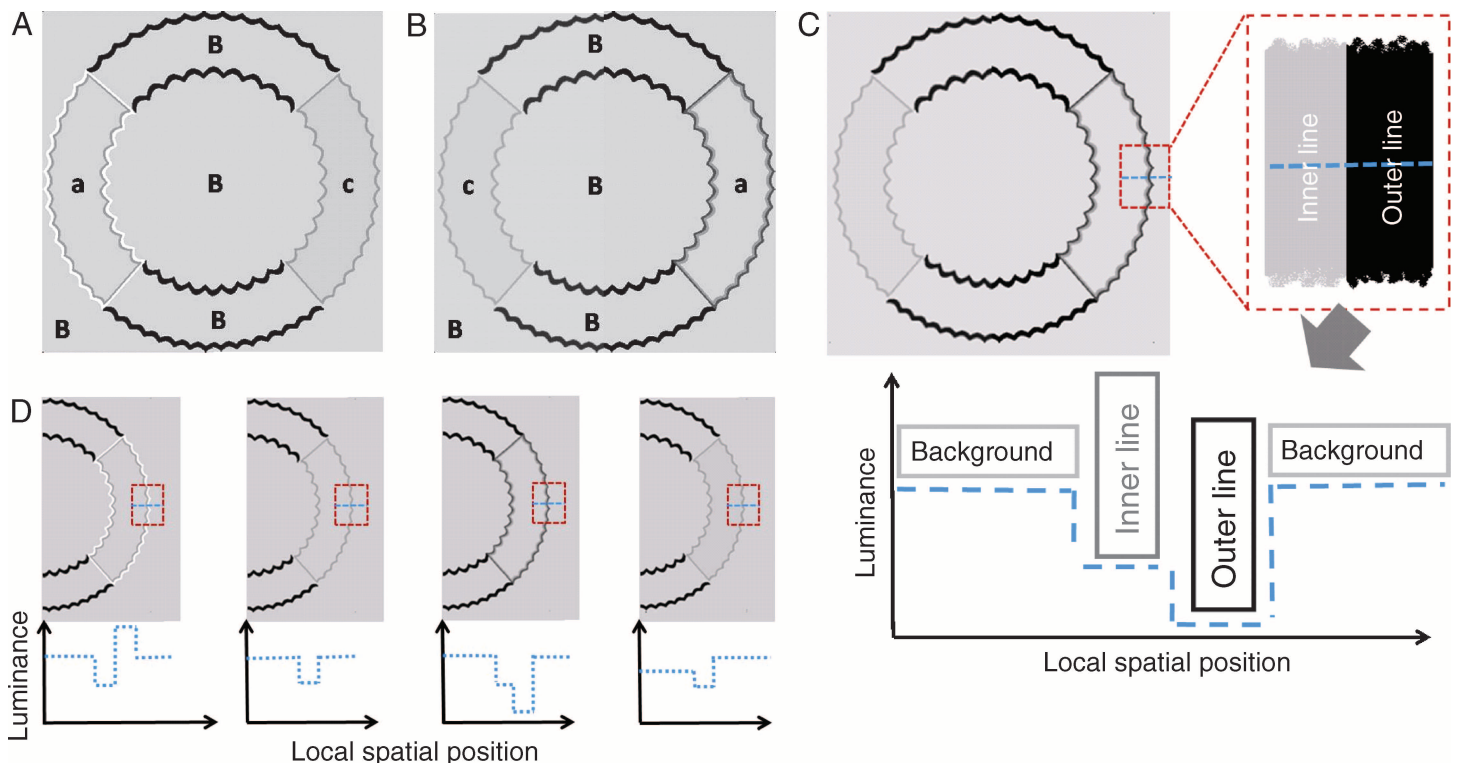

Figure 1. Samples of the stimuli and their luminance profiles. (A, B) Two sample stimuli used in the experiment. In each trial, the subject compares the darkness of regions a and c. Regions a and B have the same interior luminance. Region c is the control region, which has a lower luminance than regions a or B. Region a in (A) is enclosed by an inner line with medium luminance and an outer line with high luminance while region a in (B) is enclosed by an inner line with medium luminance and an outer line with low luminance. (C) The luminance profile of the stimulus shown in (B). The magnified part shows the luminance profile of the corresponding position. (D) Samples of stimuli with different outer lines (from left to right): high luminance, same as regions marked as a and B in (A), low luminance, and the control in which the enclosed region has a slightly lower luminance than B.

background (92 cd/m^2). The luminance of the inner line is fixed (70.5 cd/m^2) in all the stimuli, while the luminance of outer lines varies (see Figure 1D). The diameter of the annulus is about 6 degrees at a viewing distance of 57 cm.

There are nine luminance levels of outer lines in the illusory regions. Some regions contain outer lines with luminance levels higher than the background luminance. The outer lines in these regions have three luminance levels: 124.0, 114.0, and 103.5 cd/m^2. We define these as regions 1, 2, and 3, respectively. Some regions contain outer lines with luminance levels between (and including the same value as) the luminance of the background and the inner line. The outer lines in these regions have three luminance levels: 92.0, 80.0, and 70.5 cd/m^2. These are defined as regions 4, 5, and 6, respectively. Other regions contain outer lines with luminance levels lower than the inner line's luminance. The outer lines in these regions have three luminance levels: 44.3, 23.0, and 2.0 cd/m^2. These are defined as regions 7, 8, and 9, respectively.

There are three control stimuli. They contain no outer line, but the luminance of the area enclosed by the inner line is lower than the background: 91.2 (control 1), 89.7 (control 2), and 88.0 cd/m^2 (control 3), respectively. The luminance differences between control 1 and background, control 2 and control 1, and control 3 and control 2 are above the general noticeable difference for both subjects in pilot studies. These three control levels help distinguish achromatic WCE effects across a range of outer line luminances. All lines are about 4 arcmin in width. The wiggly pattern of the inner line and the outer line is useful to enhance the WCE (Pinna et al., 2001).

Each stimulus contains one test (illusory) region and one control region. All possible combinations of the test stimuli as one enclosed region and the control stimuli as the other enclosed region are shown in random order.

Procedure

Before the experiment, the subjects were dark-adapted for 2 to 3 min. Their task was to compare the darkness of the two enclosed areas in the annulus and to report which one looked darker (see Figure 1). Because pilot experiments indicated a possible confound between the perception of lightness and figure/ground distinction, we were careful to ask our subjects to focus on darkness (lightness decrement) only. The instructions were given as follows.

"In each trial, you will see one stimulus as below. Your task is to indicate which region, A (the left enclosed region [corresponding to area a in Figure 1A]) or B (the right enclosed region [corresponding to area c in Figure 1A]), is DARKER than the other, as marked on the areas within the stimulus. If A or the left one is darker, please press the 'Left Arrow' key; if B or the right one is darker, please press the 'Right Arrow' key. Please try to make a choice in

every trial. Fixate at the crossing mark whenever it appears. It will temporarily turn red after each valid response."

In each trial, the stimulus was only displayed for 150 ms. A fixation cross was shown for 500 ms before the stimulus and was shown again for 3000 ms afterward. The subjects were required to fixate at the cross during the pre-stimulus 500-ms duration, before which the trial number was displayed. The fixation cross would turn red after each recorded response.

The experiment included three sessions: a practice session including instructions and two experimental sessions, each of which contained four blocks. There were 54 trials in each block. In the practice session, the subjects saw only the control stimuli and compared the lightness of the enclosed regions. There was feedback after each response. Once their performance was higher than a preset standard of 80% correct (but their actual percentage was 91.7% on average), the first experimental session would be automatically loaded. The subjects were told that there was no feedback in the experiment sessions. Between the blocks, there was a break, of which the subjects could decide the length, while there was a required rest of 3 to 5 min between the sessions.

Subjects

All subjects had normal or corrected-to-normal vision. The subjects' consent was obtained in accordance with a protocol approved by the Boston University Charles River Campus Institutional Review Board (CRC-IRB).

Results

Figure 2 shows sample data from one subject with reference to the stimulus profiles on the left side. The numbers are indices referring to regions with different outer line luminances, from 1 to 9. A table of these indices and their corresponding luminances is provided at the bottom of Figure 2. As shown in the figure, for regions 1 to 3 the outer line and the inner line have the opposite contrast polarity compared to the background, while for regions 7 to 9 the outer line and the inner line have the same contrast polarity. For regions 4 to 6, the outer line has a luminance between the luminance of the background and the inner line or equal to one of them. Each bar on the right indicates the percentage of times that the corresponding stimulus is reported darker than control 1 by the subject.

Figure 3 shows the results of all the subjects. Each number along the horizontal axis corresponds to a region index. The data for responses to different controls are shown in different grayscales: black, control 1; gray,

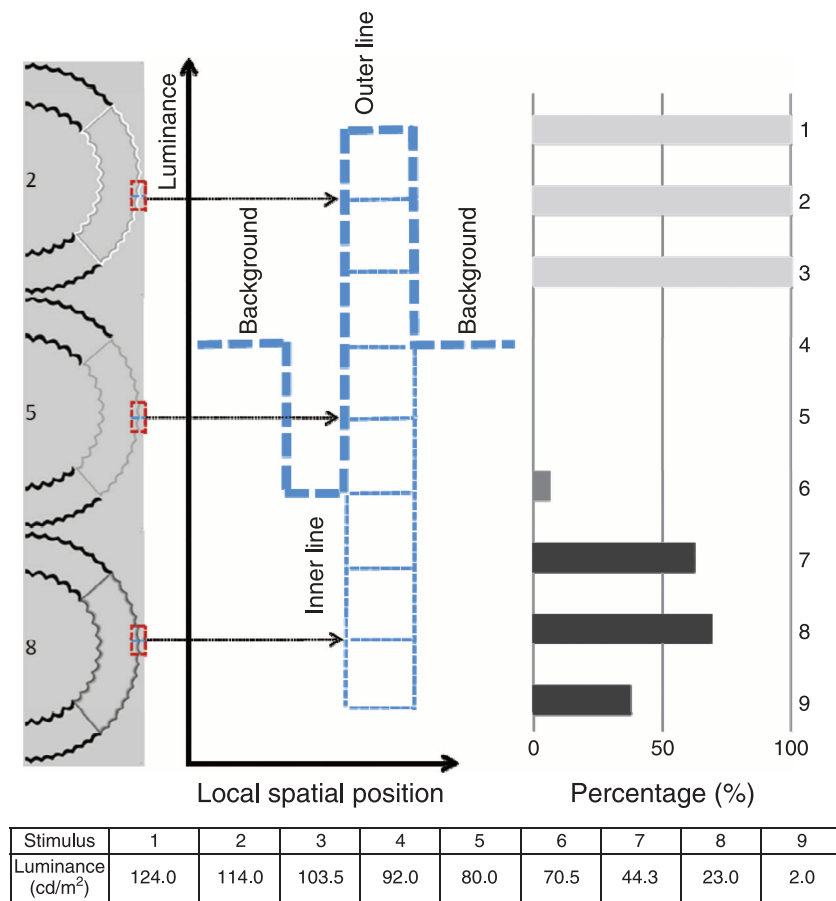| Stimulus	1	2	3	4	5	6	7	8	9
Luminance (cd/m^2)	124.0	114.0	103.5	92.0	80.0	70.5	44.3	23.0	2.0

Figure 2. A sample result from one subject, with a reference to the stimulus profile. The number is an index referring to regions with different outer line luminance, for example, 1 and 9 correspond to the regions with the outer lines of the highest and lowest luminances, respectively. Each bar on the right indicates the percentage of trials in which the corresponding region is reported darker than control 1. The bottom table gives the luminance of the outer line in each type of stimulus.

control 2; white, control 3. For each subject, we measure the percentage of each illusory region reported as darker than the three controls separately. For example, the first subplot in Figure 3 (top left corner) shows the percentage of the trials in which the illusory region 1 is reported as the darker one when it is compared with controls 1, 2, and 3 in black, gray, and white bars, respectively (the percentage is converted to 0 to 1 scale). Then, we summed these percentages, as shown in the same subplot, in which the black, gray, and white bars are stacked together (the left bar). This method provides a stable comparison among different outer line conditions. Then, the percentage means and their standard errors are divided by the maximum of the sum for each subject (normalization). Because the means usually have different overall values for different subjects, which indicates a general difference in reporting the illusion across the subjects, the normalization makes it easier to compare the result patterns across subjects than the raw data. The raw data are shown in the Supplementary materials.

The results in Figure 3 confirm that the lightness change induced in the area enclosed by the inner line and the outer

line is measurable. Furthermore, the effect is almost never the strongest when the outer line has one of the extreme luminance levels. For both polarity conditions (regions 1 to 3 and regions 7 to 9), the strength curve of the effect against the luminance level of the outer line suggests an inverted U shape that peaks at a luminance level between the extremes, although individual differences exist (see stimuli 2 and 3 compared to stimuli 1 and 4, and stimuli 7 and 8 compared to stimuli 6 and 9 in each subject's results).

In addition, similar to the chromatic WCE, when the luminance of the outer line is between the luminance of the background and the inner line, the effect is very small or even gone, provided that the luminance difference between the background and the inner line is not big enough to reverse the inducing role of the inner line and the outer line.

The results in Figure 3 also indicate that, in the current configuration of the line luminances, the induced achromatic WCE always generates a darker perception than the perceived lightness of background when the outer line has a higher or lower luminance than both the inner line and the background. For some subjects, when the outer line has a luminance higher than both the inner line and the

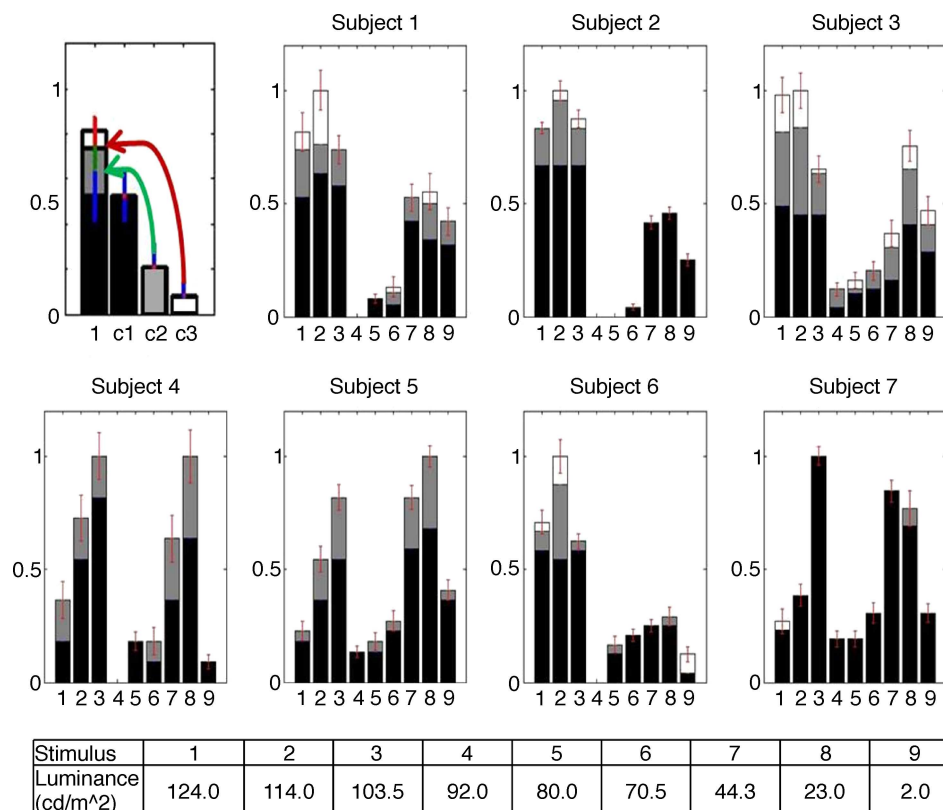| Stimulus	1	2	3	4	5	6	7	8	9
Luminance (cd/m^2)	124.0	114.0	103.5	92.0	80.0	70.5	44.3	23.0	2.0

Figure 3. Contrast effect: The results of all the subjects for all the stimuli compared to 3 controls. Each bar indicates the percentage (in a [0, 1] scale) of the trials in which the corresponding stimulus is reported as darker than a certain control by the subject as explained in the text. The results using three controls are shown in different grayscale: black, control 1; gray, control 2; white, control 3. The error bars shown are the mean among the three control conditions in each stacked bar. The bottom table gives the luminance of the outer line in each type of the stimulus.

background, the achromatic WCE is stronger than that when the outer line has a luminance lower than both the inner line and the background.

Discussion

The achromatic WCE is measurable

We have developed a method to measure the strength of the WCE in the achromatic domain by using paired comparisons with multiple references. Since the comparison is made between an illusory region and a control region with real luminance change in the corresponding area, the results confirm a lightness illusion. Most previous studies on the WCE address the effect in chromatic domain (Devinck, Hardy, Delahunt, Spillmann, & Werner, 2006; Pinna et al., 2001; Pinna, Werner, & Spillmann, 2003) and some researchers suggest that the WCE should be considered as "a predominantly chromatic effect" since no luminance adjustments are necessary to match the

illusory stimuli (Devinck et al., 2005). As mentioned in those articles, although the WCE is perceptually salient for the subjects, it is not easy to capture the illusion in a quantitative way. We can imagine that it is even harder to measure the effect in the achromatic domain. During pilot studies, we tried several configurations to enhance the effect and make it easy to measure. In one study, we found that matching was not an ideal way to measure the achromatic WCE, because the effect was weak and the subjects easily got adapted to the stimuli, and thus the interaction of the adaptation effect and the illusory lightness effect could make the decision standard of the subjects unstable. When we developed the reported configuration and paradigm, we found that we were able to make the achromatic WCE reliably measurable.

Contrast effect

The luminance or the contrast difference between the two lines is crucial to generate the effect (Pinna et al., 2001). Some studies show that the bigger the difference, the stronger the effect, and when the two lines have equal

luminance, the effect is weak and hard to see (Devinck et al., 2005). However, those studies did not use a contrast range that includes both polarities against the background.

In our study, the luminance of the inner line is fixed close to a mid-level between the maximum (white) and minimum (black) luminances, while the luminance of the outer line is varied from high luminance to low luminance. It is clear in the results that when the luminance of the outer line is between the luminance of the inner line and the background, the effect is very weak or even gone, which is consistent with the chromatic WCE. However, given a certain contrast polarity pattern of the two lines, the effect is almost never the strongest when the luminance difference between the outer line and the inner line is the largest, which is the case when the outer line is white or black. The strength of the effect usually peaks at a medium luminance-difference level and becomes weaker when the outer line luminance goes near or becomes the same as that of the inner line or the background. So if we assume that it is the luminance difference between the outer line and the inner line that causes the effect, then the relation between the luminance difference and the strength of the effect is certainly not linear or even monotonic according to our results (see Grossberg & Mingolla, 1985; Pinna & Grossberg, 2005, for a proposed model, in which the outer line surrounding the enclosed area suppresses the boundary signal of the inner line, thereby permitting the color or lightness signal of the inner line to affect the background region). However, due to the difference of visual system response to chromatic and achromatic stimuli, it is possible that the contrast effect we observe in the current study is not exactly the same as that of chromatic stimuli.

Polarity effect

The current results indicate that we could observe the achromatic WCE when the luminance of the outer line is higher than the luminance of the background and the inner line (opposite luminance contrast polarity for inner and outer lines against background, or "opposite polarity") as well as when the luminance of the outer line is lower than the luminance of the background and the inner line (same luminance contrast polarity for inner and outer lines against background, or "same polarity"). These results suggest that the WCE is not simply caused by the absolute value of the luminance difference between the inner line and the outer line, because the absolute value of that difference is much smaller for the "opposite polarity" condition than that for the "same polarity" condition.

Although there is an apparent assimilation effect in the chromatic WCE, it is hard to tell whether it is actually assimilation or some type of contrast effect happening here for the "opposite polarity" condition, since several studies show that although the contrast and assimilation conditions have opposite lightness effects compared to each other, they may actually induce a lightness change in the same direction (say darker) when they are compared to the same standard stimuli (Beck, 1966; De Weert & Spillmann, 1995; Hamada, 1984; for data concerning the effect of the width and separation of the lines on assimilation and contrast, see Fach & Sharpe, 1986; Helson, 1963).

In Figure 4, we further display data for the achromatic WCE for the "opposite polarity" condition (bars marked with "2 + 3") and the effect for the "same polarity" condition (bars marked with "7 + 8"). The data are
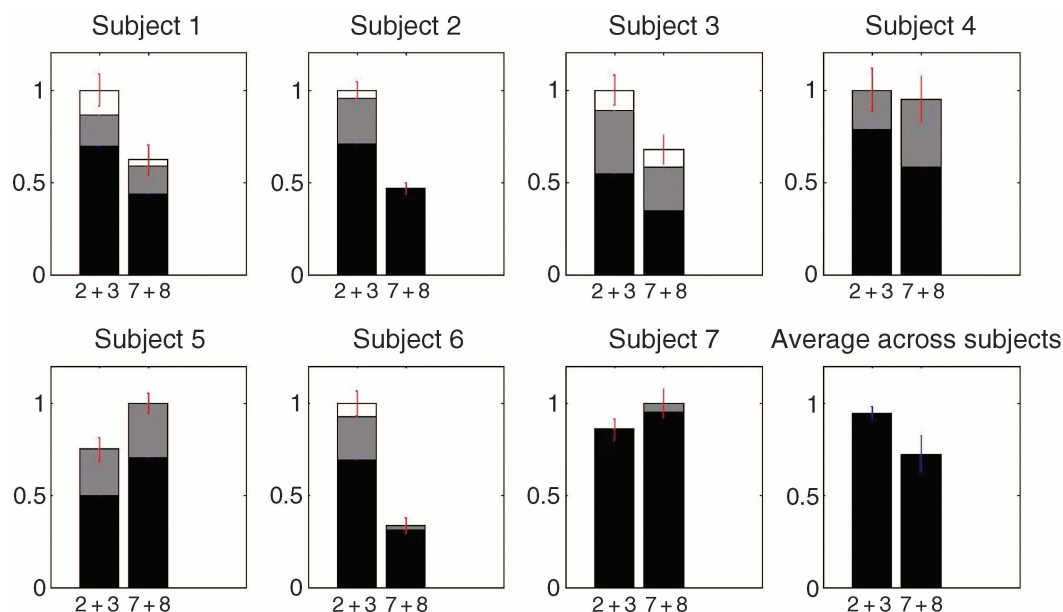

Figure 4. Polarity effect for the outer line: The strength of the WCE in the stimuli with opposite luminance polarity of the outer line and the inner line against the background (region 2 and 3 versus 7 and 8). Each bar indicates the percentage (in a [0, 1] scale) of the trials in which the corresponding stimulus is reported as darker than a certain control. The colors used here represent the same data as that in Figure 3.

normalized as in Figure 3, for direct cross-subject comparison. For some subjects (subjects 1, 2, 3, and 6), the stimuli with the outer lines that have an opposite contrast polarity compared to the inner line generate a significantly stronger effect than those with outer lines that have the same contrast polarity with the inner line. However, for the other subjects, this effect is not significant. Interestingly, all the subjects (subjects 1, 2, 3, and 6) that show this polarity effect perceive the achromatic WCE more strongly than the other subjects, since these subjects (subjects 1, 2, 3, and 6) show a floor effect for control 1.

The WCE and the Craik–O'Brien–Cornsweet effect

The WCE and the Craik–O'Brien–Cornsweet Effect (COCE) could be regarded as related, because the luminance profile of the stimuli of the WCE is like a discrete version of the stimuli of the COCE, or the stimuli of the WCE are similar to a partially blurred version of the COCE stimuli (see Figure 5). However, as shown in Figure 5 (red solid line: WCE; blue dashed line: COCE), the line used in the WCE in this study and some of other studies (Pinna et al., 2001) is much thinner in spatial scale compared to the gradients in the COCE stimuli. Todorović (2006, Figures 9a–
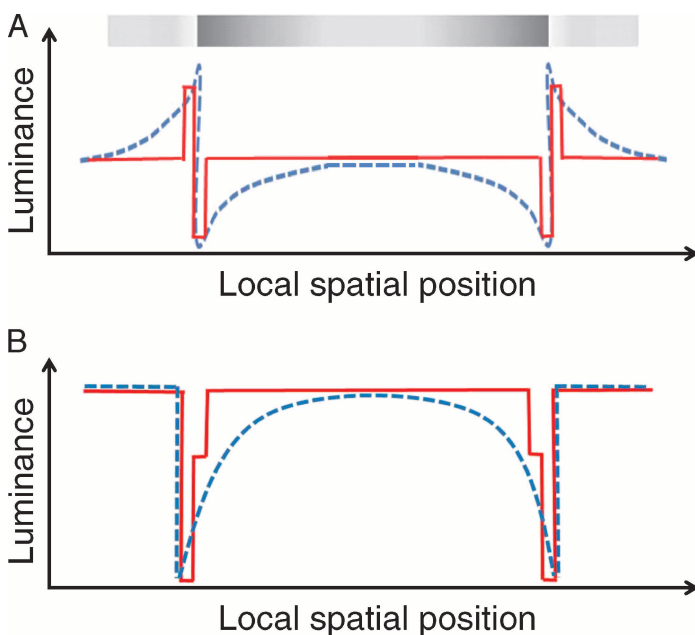

Figure 5. Luminance profiles of WCE and COCE stimuli. (A) A WCE stimulus with opposite contrast polarity between the outer line and the inner line and its corresponding COCE stimulus. The spatial scale shows the comparison of the line width in WCE and the typical gradients in COCE. The grayscaled bar on top shows the sample with the profile of COCE. (B) A WCE stimulus with the same contrast polarity between the outer line and the inner line and its corresponding COCE stimulus.

9f) also noticed this connection between the WCE and the COCE and he discussed the effect of gradients and corresponding coarse (discrete) versions in general cases.

Todorović (1987) showed that there is an asymmetry of the effects of outward-gradient and inward-gradient variations of the COCE stimuli. This asymmetry may suggest that even in the double-gradient figures of the COCE, the two gradients might contribute unequally to the lightness perception. The fact that the outward-gradient stimuli induce a stronger lightness change than the inward-gradient stimuli may also suggest a possible role of simultaneous contrast in the COCE. Considering two typical configurations of the WCE that we use in this study and their corresponding COCE stimuli as shown in Figure 5, and given the fact that the configuration in Figure 5A induces a bigger lightness change than the configuration in Figure 5B, it is reasonable to wonder whether the COCE and WCE may share common mechanisms. These mechanisms of lightness perception could be shared among neurons with different spatial frequency tunings.

Measurement of the WCE

Salient perception versus weak effect

A previous study on the chromatic WCE has already noted that the effect is perceptually salient but hard to measure (Devinck et al., 2005). The reason for this phenomenon may be due to the following facts: (1) the effect is not strong on a relatively large homogeneous surface. As shown in one chromatic WCE experiment, large hue shifts were required to nullify the color of stimuli only when the width of area between inducing lines is less than 9.3 arcmin (Devinck, Delahunt, Hardy, Spillmann, & Werner, 2006). The effect exponentially decreases when the width between inducing lines increases up to 7.4 deg. Thus, though the effect is quite noticeable in perception, it may be hard to measure when the area is not small enough. (2) The weak effect on a large surface may also generate rapid adaptation effects, which makes it hard to measure when it is shown for periods longer than a few hundred milliseconds. (3) The WCE can also generate a figure–ground effect that interferes with the lightness effect, as is next described.

Lightness versus surface effect

In our experiment, the subjects were asked to tell which of the two regions is darker. This is in the domain of lightness. However, the WCE can generate a surface effect as well, which means that the WCE will enhance the perception of the region enclosed by the outer line and the inner line as a figural surface. However, according to our pilot studies, the surface effect is not always consistent with the lightness effect in the achromatic WCE, as suggested by some other studies (von der Heydt & Pierson, 2006). That is to say, sometimes the configuration generating a strong surface (figure–ground) effect might not generate a

strong effect in lightness at the same time and vice versa. In our pilot studies, we noted that sometimes observers were prone to confound the two effects when responding.

Conclusion

We have confirmed the existence of the achromatic WCE. However, surprisingly, the achromatic WCE does not show a monotonic increase of effect strength when the luminance difference of the outer line and the inner line increases. The effect strength seems to reach a peak and then decrease after the luminance difference goes beyond a certain level. The achromatic WCE does not show a weaker effect when the outer line and the inner line have an opposite contrast polarity against the background than when they have the same polarity.

The interaction of the mechanisms underlying boundary and surface perception is an essential problem for vision scientists. The achromatic WCE is one interesting example, in which only two thin achromatic lines can induce a lightness effect over a large range. The ability to measure a lightness effect in such configurations can help advance our knowledge of boundary and surface perception in general.

Acknowledgments

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