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Last but not least

Watercolor illusion induced by synesthetic colors

1 Introduction

Synesthesia, which literally means a mixing of the senses, takes on various forms, but the most common is the experience of color when viewing achromatic alphanumeric characters (Day 2005; Rich and Mattingley 2002). Called 'color-graphemic synesthesia', this condition has attracted great interest recently, in part because of its potential implications for understanding neural plasticity and cortical modularity (Grossenbacher and Lovelace 2001). The colorful, mystifying verbal descriptions offered by color-graphemic synesthetes suggest that synesthetic colors are as salient and as perceptually real as the experiences enjoyed by non-synesthetes when viewing real-colored objects. Moreover, there is a growing body of evidence in support of this equivalence, evidence showing that synesthetic colors behave like real colors on a variety of perceptual tasks.

It is known, for example, that color-graphemic synesthetes can segregate a figure from its background on the basis of synesthetic colour (Palmeri et al 2002; Ramachandran and Hubbard 2001a). Color-graphemic synesthetes also tend to group achromatic letters of the same synesthetic color when viewing apparent-motion animations (Ramachandran and Hubbard 2005) and when viewing multi-element binocular rivalry displays (Kim et al, forthcoming). In addition, color-graphemic synesthetes exhibit a synesthetic 'Stroop' effect: they are slower at naming the color of ink in which words are printed when those ink colors are inconsistent with the individual's associated synesthetic colors (Dixon et al 2000; Odgaard et al 1999).

In our laboratory, one telltale indicator of the perceptual reality of synesthetic colors was provided by the discovery of a synesthetic McCollough effect. As described by McCollough (1965), people experience an orientation-contingent color aftereffect following prolonged, sequential adaptation to orthogonally oriented gratings differing in color. We adapted two color-graphemic synesthetes alternately to horizontal and to vertical 'gratings', the contours of which were composed of achromatic letters whose spacing clearly defined orientation of the contour. The letters themselves for the two gratings were selected so as to generate synesthetic colors of red and green for horizontal and vertical, respectively. This adaptation regime failed to produce any hint of a McCollough effect in non-synesthetic observers, which is not surprising. In the two synesthetes, however, it produced the same pattern of illusory, opponent colors as those produced by adaptation to real-colored gratings (Blake et al 2005). Unfortunately, the McCollough effect requires an extended period of adaptation, and the effect itself tends to be rather weak (ie the illusory colors are highly desaturated). Moreover, this synesthetic McCollough effect is remarkably enduring: one of our synesthetes reports that she still perceives her synesthetic McCollough colors almost a year after our initial adaptation experiment! The real McCollough effect, too, is remarkably long-lasting (Jones and Holding 1975). The enduring nature of the McCollough effect makes it very difficult to administer multiple, independent trials. It was gratifying, therefore, to find that another, equally compelling color illusion—the watercolor effect—could also be induced by synesthetic colors—an illusion that lends itself readily to standard psychophysical analysis. It is the synthesthetic version of this illusion that we report in this paper.

2 The watercolor illusion

Several years ago Pinna and colleagues (Pinna et al 2001) described a fascinating form of color induction they called the 'watercolor effect'. When a dark-colored (eg purple) wavy contour surrounds a lighter-colored (eg orange) wavy contour, the lighter color appears to spread within the achromatic area enclosed by the contour; spreading is not seen, however, when the lighter contour encloses the darker one. Figure 1a shows an example of these two configurations.

Inspired by this compelling illusion, we created a synesthetic version of one of the configurations producing the watercolor effect. Shown in figure 1b, two curved contours are composed of closely spaced, achromatic letters that induce synesthesia. We deliberately selected letters that appeared purple and letters that appeared orange to the two synesthetic observers available to us (LR and WO)—these are individuals we have been testing for several years now (see Blake et al 2005). When we showed each of these individuals a pair of these figures, made with achromatic inducers tailored to evoke orange and purple, both synesthetes spontaneously described the interior region of one figure (ie the one whose enclosed letters evoked synesthetic orange) as "faint gold" and the interior region of the other figure (ie the one whose enclosed letters evoked synesthetic purple) as "white". We also created a similar stimulus configuration in which the outer contour consisted of achromatic letters that appeared purple and the inner contour consisted of achromatic letters that appeared red to our two synesthetic observers. Both observers described the interior region of this figure as "weaker" in color (WO) or "lighter" in appearance (LR) than the interior region of the figure whose inner contour was composed of "orange" letters. These reports are consistent with watercolor experiences induced by real-colored stimuli (Pinna et al 2001). Incidentally, neither LR nor WO had ever heard of the watercolor illusion. Both individuals also readily experienced the version produced by real-colored contours, and they reported that the interior of the synesthetic version appeared more washed out in color.

This phenomenological observation was encouraging, for the watercolor effect lends itself to quantitative psychophysical testing. Following the discovery of the watercolor effect, Pinna et al (2003) showed that this illusion strongly influences figure–ground organization: the surface region into which illusory color spreads stands out as a 'figural region' relative to the achromatic background. Knowing from previous work that synesthetic observers can use their colors for figure–ground segmentation (Ramachandran and Hubbard 2001a), we asked whether LR and WO could discern an 'oddball' synesthetic watercolor figure among an array of other figures that do not engender illusory surface colors. As the following experiment reveals, the answer is "yes".

3 Methods

LR and WO are both 'projectors' (Dixon et al 2004), meaning that they see their synesthetic colors located in visual space on the alphanumeric characters themselves; thus, for example, the letter 'B' printed in black ink actually looks orange to LR, and the letter 'R' looks purple to her. Synesthetes in another category, called 'associators' (Dixon et al 2004), report seeing their colors "in the mind's eye" (implying somewhere in the head) and not on the alphanumeric characters themselves. Although both forms of color-graphemic synesthesia are rare, associators are more common than projectors in our experience. For purposes of comparison, two non-synesthetic observers were also tested; one of these non-synesthetic observers, CK, was tested with the stimulus display tailored for LR; and the other, JL, was tested with the stimulus display tailored for WO. These non-synesthetic observers were matched to the two synesthetic observers in gender, age, and education level.

All four observers—LR, WO, CK, and JL—were tested on three conditions of an oddball detection task in which one of four figures was different from the other three in terms of the configuration of alphanumeric characters comprising the figure. On each trial, the observer viewed a quartet of circles on a video monitor screen and, as quickly as possible, pressed one of four buttons indicating the location of the 'oddball' circle. Reaction time (RT) and accuracy were recorded on each trial. Observers were free to move their eyes while viewing the four images comprising a display.

Figure 2a shows examples of stimulus displays used for LR in the real-color, synesthetic, and control conditions. In the real-color condition, each of the four circles contained the typographical characters '&' and '#' presented in the actual colors orange and purple; those real colors closely matched the hue and saturation of the synesthetic colors experienced by LR and WO when viewing the appropriate inducers. These two typographical characters were used because neither character induces synesthetic color experiences for the two synesthetes. On half of the trials, a circle comprising purple #s surrounded by orange &s constituted the oddball (the other three circles being orange &s surrounding purple #s). On the other half of the trials, the oddball was a circle comprising orange &s surrounded by purple #s. In the synesthetic condition administered to a synesthete LR and to a matched non-synesthete CK, we used achromatic Rs (purple for LR) and achromatic Bs (orange for LR) to create the four circular figures forming the array. On half of the synesthetic trials, one of the four circles consisted of Rs surrounded by Bs and the other three circles consisted of Bs surrounded by Rs. On the other half of the trials, the oddball consisted of Bs surrounded by Rs. For the other synesthete, WO, and a matched non-synesthete, JL, the digit 2 (orange for WO) and the digit 8 (purple for WO) were used to create the same two categories of displays described for LR. The control condition used the same stimuli as those used in the real-color condition except that # and & appeared as gray characters against a white background (comparable to the synesthetic condition). For the control condition, all observers had to rely on character configuration to find the oddball, since there was no color—either real or synesthetic—associated in this condition.

Stimuli were presented on a 21-inch NEC monitor (1024 × 768 resolution, 75 Hz frame rate) under the control of MATLAB running on a Macintosh G4 computer. An individual character within the display subtended 19 min of arc × 19 min of arc, and the inner radius of each circle subtended 1.91 deg visual angle from a viewing distance of 90 cm. The observer initiated each trial by pressing a key that triggered presentation of the four circles. The stimulus presentation was terminated by the observer's button press indicating which one of the four circles constituted the oddball. Within a 96-trial block, the three test conditions were intermixed, with the order of the trials being haphazard within the limits of the MATLAB randomization routine. The position of the oddball circle also varied randomly from trial to trial. Each observer completed 4 blocks.

4 Results

Results showed that average RTs ranged from 1300 to 4000 ms; overall, WO and JL produced longer RTs for all three conditions compared to LR and CK, an overall slowing that may be attributable, in part, to WO and JL being about 30 years older than LR and CK. To allow direct comparison of all results, we normalized each observer's RT data by dividing each value by the mean for that observer. The bar graphs in figure 2b show the mean normalized RT for locating the oddball in the real-color, synesthetic, and control conditions, for the two synesthetes and the two non-synesthetes.

The pattern of results was identical for the synesthetic observers, differing in one important respect from the results of the non-synesthetic observers: both LR and WO showed faster RTs in both real-color and synesthetic conditions compared to the control condition, whereas nonsynesthetic observers showed faster RTs in the real-color condition only [for these two individuals, RTs in the synesthetic and control conditions were not significantly different (Fisher's least-significant-difference (LSD) test, $p = 0.132$)].

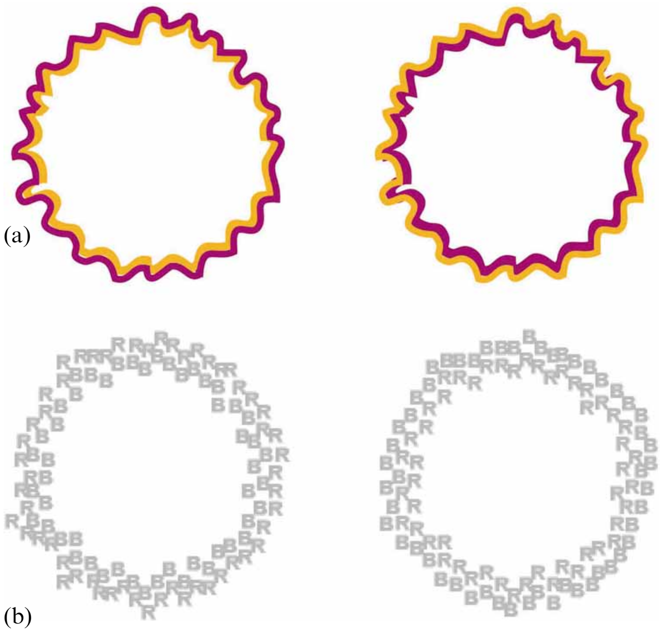

Figure 1. (a) The *watercolor effect*. Readers should be able to see yellowish color spreading within the left-hand figure but not within the right-hand one. (b) A synesthetic watercolor test for one of our synesthetic observers, LR: the letter 'B' appears orange and the letter 'R' appears purple for LR. LR sees the watercolor illusion induced within the left-hand circle but not within the right-hand circle, and she spontaneously reported these observations before ever being shown a real-watercolor display like the one in (a).

For both LR and WO, RTs in the synesthetic condition were significantly faster than RTs in the control condition, but they were significantly slower than RTs in the real-color condition. An analysis of variance (ANOVA) was performed with condition (real color, synesthetic, control) as the factor and normalized RTs as the dependent variable. The analysis revealed a significant effect of condition ($F_{2,755} = 131.819$, $p < 0.0001$ for synesthetic observers and $F_{2,752} = 362.859$, $p < 0.001$ for non-synesthetic observers). Fisher's LSD test showed significant differences between real-color and control ($p < 0.0001$), between synesthetic and control ($p < 0.0001$), and between real-color and synesthetic r ($p < 0.0001$) conditions for synesthetic observers. For non-synesthetic observers, however, the analysis showed only significant differences between real-color and control ($p < 0.0001$), and between real-color and synesthetic ($p < 0.0001$) conditions.

These differences in RT did not arise from variations in the accuracy of performance (as indexed by the percentage of trials on which the observer selected the correct alternative out of the four possibilities). All observers showed high accuracy, near ceiling, in all three conditions (LR: 99.44% in the real-color, 97.66% in the synesthetic, and 100% in the control conditions; WO: 95.97% in the real-color, 95.24% in the synesthetic, and 96.77% in the control conditions; non-synesthetes: 99.20% in the real-color, 98.01% in the synesthetic, and 96.05% in the control conditions).

One might ask why RTs to the synesthetically colored displays were considerably longer than RTs to the real-colored displays for LR and WO. Recall that both individuals reported that the spreading color induced by synesthetically colored characters appears more washed out than does the spreading color produced by real-colored characters. Perhaps, then, this washed out color is responsible for the slower RTs in the synesthetic condition. To examine this hypothesis, we tested non-synesthetic observer CK

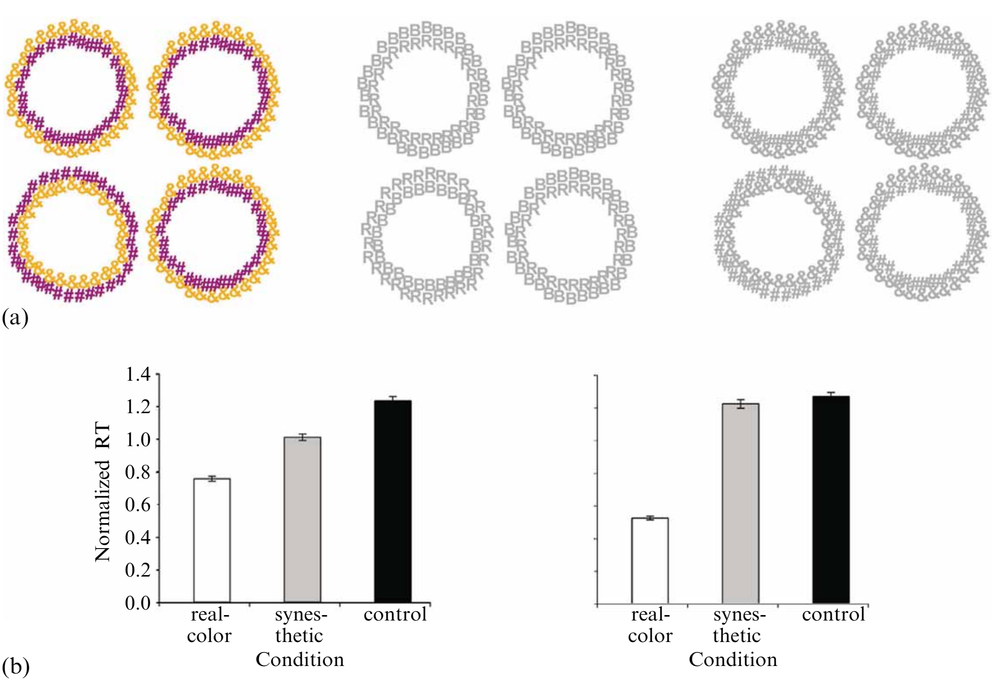

Figure 2. (a) Sample stimulus displays shown as the real-color (left), synesthetic (middle), and control (right) conditions for LR: observers were to find the oddball among the four circles. The oddball (bottom left in these examples) was different from the others only in that its inside and outside borders were switched. (b) Normalized RT from the oddball detection task: white bars represent the averages from the real-color condition, gray bars represent averages from the synesthetic condition, and black bars represent the averages from the control condition. Vertical bars denote ±1 mean standard error. The graph on the left shows averaged results from two synesthetic observers (LR and WO) and the graph on the right shows averaged results from two non-synesthetic observers (CK and JL).

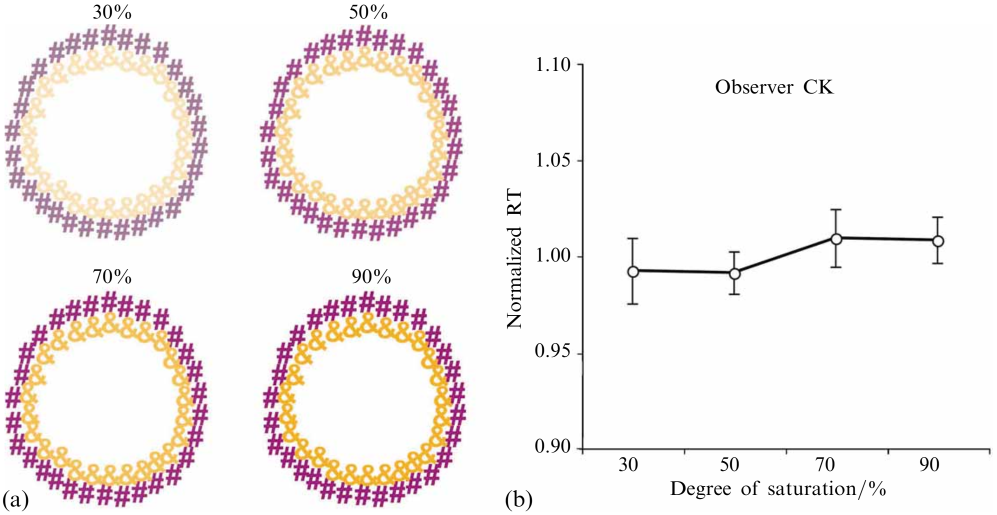

Figure 3. Sample figures that induce watercolor effect in four different degrees of color saturation (30%–90%; the circle with 90% saturation was the same figure as used in the real-color condition in the main experiment): the non-synesthetic observer (CK) was either to find the inducing circle among the other three non-inducing circles or to find the non-inducing circle among the other three inducing circles. (b) Normalized RT from the oddball detection task with degrees of color saturation varied. Vertical bars denote ±1 SEM.

using real-colored inducing stimuli like those shown in figure 3a.(1) Four different degrees of color saturation were tested, with the order of saturation values varying randomly over trials. All other aspects of the oddball task were the same as in the main experiment. RT did not differ among the four degrees of saturation (figure 3b): an ANOVA showed no statistically significant effect of saturation degrees ($F_{3,\,502} = 0.493$, $p = 0.687$). These results provide no support for the hypothesis that washed-out color within the interior is responsible for the slower RTs in the synesthetic condition.

5 Discussion

Both phenomenological report and forced-choice RT testing reveal that synesthetic colors can induce a robust watercolor effect. Accordingly, these results add yet another link in the chain connecting color-graphemic synesthesia to genuine color perception. It is no longer reasonable to construe synesthesia as the result of conceptually triggered, over-learned associations between color names and alphanumeric characters.(2) If LR and WO were merely 'thinking' about their colors when they viewed achromatic letters/digits, why would they more quickly localize oddballs in the synesthetic condition than in the control condition?

Others have found that synesthetic colors, while vivid, are not as potent as real colors when it comes to performance on tasks like figure–ground segregation (eg Hubbard et al 2005). Our results, too, show this disparity between real and synesthetic colors: recall that the watercolor effect produced by synesthetic inducers yielded longer RTs than did the watercolor effect produced by real-colored inducers. This difference in RTs cannot be attributed to desaturation within the interior (figure 3). Moreover, these differences were found even though accuracy was equivalent for both conditions and, phenomenologically, the synesthetically colored characters were as vivid as the real colors. These lengthened RTs could arise from the additional processing time needed to recognize the inducing stimuli. To the extent that recognition requires awareness or attention, our findings are consistent with the hypothesis that awareness and/or attention are prerequisites for experiencing synesthetic colors (Mattingley et al 2001; Rich and Mattingley 2005; Sagiv and Robertson 2005). This hypothesis is controversial, however—for at least some synesthetes, synesthetic colors do seem to be perceived preconsciously and preattentively (Ramachandran and Hubbard 2001b; Smilek et al 2005).

Regardless of the role of awareness and attention, it is clear that synesthetic colors, when they are experienced, provide a perceptual advantage when it comes to identifying an oddball figure among a set of distractors. The challenge now becomes to understand the neural concomitants of the color sensations that promote this advantage. It is tempting to conclude that synesthetic colors arise from activation of neural structures ordinarily involved in real-color perception, and there are some brain-imaging data pointing to that kind of involvement (eg Hubbard et al 2005; Nunn et al 2002). It also remains to be seen whether the synesthetic watercolor illusion can be produced in associators, that class of individuals who do not experience colors on the characters themselves (Dixon et al 2004).

Chai-Youn Kim, Randolph Blake
Department of Psychology, Vanderbilt Vision Research Center, Vanderbilt University, Nashville, TN 37203, USA; e-mail: chai-youn.kim@vanderbilt.edu

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(1) By varying the saturation of these colored inducers, we were not attempting to mimic the synesthetic colors of the inducers experienced by WO and LR but, instead, to mimic the color spreading they experience within the interior of the figure.

(2) Learning undoubtedly plays some role in color-graphemic synesthesia, for the stimuli evoking color sensations—letters and digits—are limited to culturally familiar human artifacts (Marks and Odgaard 2005).

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