Supplemental Data: Filling-in afterimage colors between the lines

Rob van Lier, Mark Vergeer, and Stuart Anstis

This document describes the methods and results of our two experiments in greater detail. The first is a color matching experiment (3 observers, the procedure and results were briefly described in Figure 1 of the Correspondence); the second is a color judgment experiment on a larger range of color settings (15 observers).

SUPPLEMENTAL EXPERIMENT 1

Stimuli and procedure

An adapting 8-pointed colored star alternated over time with two successive achromatic test outlines (see Figure 1, Supplementary Movies 2a and 2b). The colored star comprised two 4-pointed stars (upright versus oblique) whose points could have one of two colors: red (CIE (x,y) = 0.3768, 0.3285; L= 41.91 cd/m^2) or cyan (CIE (x,y) = 0.2597, 0.3330; L= 40.95 cd/m^2). The center of the adapting star was grey (CIE (x,y) = 0.3054, 0.3187; L= 42.87 cd/m^2), the background was of a lighter grey (CIE (x,y) = 0.3119, 0.3279; L= 58.13 cd/m^2). The colors were balanced across the two component stars (upright red star / oblique cyan star; upright cyan star / oblique red star). The adapting 8-pointed colored star alternated with two achromatic test outlines, each one corresponding with one of the 4-pointed stars. The 8-pointed colored star was presented for 1000 ms and the test outlines for 500 ms each. With respect to each test outline we distinguish 2 different color settings: the red patches of the previously presented colored star would fall inside the outline whereas the cyan colored patches would fall outside that outline (i.e. the R_iC_o condition), and vice versa (C_iR_o). During the test phase, a second achromatic outline, the "matching outline", appeared simultaneously with one of the test outlines and was presented next to the test outline. This matching outline was filled with an adjustable color mix that was under the observer's control. The task of the observers was to adjust the color of the inner area of the matching outline until its color matched the perceived afterimage color in either the first or the second test outline. Thus, there were 8 unique stimuli: 2 colored star configurations; 2 temporal orders of test outlines; 2 matching outline appearances (simultaneously with the first or the second test outline). All stimuli were presented 4 times, so 8x4=32 adjustments were required.

The field inside the matching outline was adjustable by means of keyboard buttons, modulating the RGB values. The observers could take as much time as they wished for each match, and, if necessary, they could reset the adjusted RGB values to restart the adjustment for each specific stimulus, until they were satisfied and definitely entered the adjusted RGB values. The stimuli were shown on a 19” monitor (100Hz), which was first calibrated using the X-Rite Monitor Calibrator. The visual angle of the star subtended 5.5°, and the afterimage and matching outlines were spaced 6.3° apart between the centers.

Participants

Three observers participated in this experiment. Two observers were expert viewers and authors of this correspondence (RL, MV). The third observer was a naive non-expert viewer (JW).

Results

We have determined the CIE(x,y) values for all adjustments and calculated the difference from the background CIE(x,y) values ($dx = x_{adjusted\ field} - x_{background}$; $dy = y_{adjusted\ field} - y_{background}$, where $x_{background}$=0.3119 and $y_{background}$=0.3279) per color setting per participant. In Table 1, for each participant the dx and dy values are given for the conditions R_iC_o-I (Red-inside/Cyan-outside/First-outline), C_iR_o-I (Cyan-inside/Red-outside/First-outline), R_iC_o-II (Red-inside/Cyan-outside/Second-outline), C_iR_o-II (Cyan-inside/Red–outside/Second-outline). A MANOVA analysis confirmed that for each of the observers, for each of the above conditions, the adjustments differed from the background (see Table S1A for details). An additional analysis confirmed that for each of the observers, the adjustments on R_iC_o-I differed from C_iR_o-I, and the adjustments on

R_iC_o-II differed from C_iR_o-II (See Table S1B for details). That is, the results confirm the initial observation that the R_iC_o setting induces a more cyanish afterimage and the C_iR_o setting a more reddish afterimage.

Table S1A, adjustments per participant

R_iC_o-I	C_iR_o-I	R_iC_o-II	C_iR_o-II
		pp1 (RL)	
dx= -.0044	dx= .0034	dx= -.0029	dx= .0033
dy= .0005	dy= .0016	dy= .0007	dy= .0015
F(2,6)=138.9	*F(2,6)*=40.4	*F(2,6)*=18.2	*F(2,6)*=86.6
p<.0001	*p*=.0003	*p*=.0028	*p*<.0001
		pp2 (MV)	
dx= -.0044	dx= .0051	dx= -.0024	dx= .0033
dy= -.0005	dy= .0003	dy= .0007	dy= .0001
F(2,6)=57.6	*F(2,6)*=223.3	*F(2,6)*=148.8	*F(2,6)*=213.4
p<.0001	*p*<.0001	*p*<.0001	*p*<.0001
		pp3 (JW)	
dx=-.0091	dx= .0110	dx= -.0075	dx= .0070
dy=-.0006	dy= .0004	dy= -.0001	dy= .0003
F(2,6)=165.9	*F(2,6)*=31.4	*F(2,6)*= 37.9	*F(2,6)*=155.1
p<.0001	*p*=.0007	*p*=.0004	*p*<.0001

Note. For each of the participants and for each condition (color-setting x outline-number), the adjustment in CIE (x,y) color space is shown (dx= $x_{adjusted\ field} - x_{background}$; dy= $y_{adjusted\ field} - y_{background}$, where $x_{background}$=0.3119 and $y_{background}$=0.3279). R_iC_o-I: Red-inside/Cyan-outside/First-outline; C_iR_o-I: Cyan-inside/Red-outside/First-outline; R_iC_o-II: Red-inside/Cyan-outside/Second-outline; C_iR_o-II: Cyan-inside/Red-outside/Second-outline.

Table S1B, adjustments per participant

R_iC_o-I ~ C_iR_o-I	R_iC_o-II ~ C_iR_o-II
pp1 (RL)	
$F(2,13)$=150.4 p<.0001	$F(2,13)$=73.8 p<.0001
pp2 (MV)	
$F(2,13)$=204.2 p<.0001	$F(2,13)$=171.1 p<.0001
pp3 (JW)	
$F(2,13)$=93.4 p<.0001	$F(2,6)$=130.0 p<.0001

Note. For each of the participants and for both outlines (first and second) the matching reveals clearly different afterimage colors for the two color settings. R_iC_o-I: Red-inside/Cyan-outside/First-outline; C_iR_o-I: Cyan-inside/Red-outside/First-outline; R_iC_o-II: Red-inside/Cyan-outside/Second-outline; C_iR_o-II: Cyan-inside/Red-outside/Second-outline.

SUPPLEMENTAL EXPERIMENT 2

In this experiment we used a broader variety of adapting colors. In all trials, a colored stimulus alternated with a single test outline.

Stimuli

The 8-pointed star configurations were the same as in Experiment 1. The colors, however, were different and were drawn from the Teufel-Wehrhahn color set (*S1*). This set contains 16 colors that were selected to be isoluminant, perceptually equidistant and equally detectable. From this color set, four colors were used in the stimuli. These colors are positioned along two orthogonal axes in color space, to be referred to as Purple (P), Cyan (C), Green (G), and Red (R). CIE(x,y) coordinates are P: (0.278, 0.259); C: (0.284, 0.332), G: (0.345, 0.407); R: (0.322, 0.303), respectively. The conditions were as follows. <u>Number of Colors</u> (One Color versus Two Colors). In the One-Color condition the points of just one of the 4-pointed component stars were colored in one of 4 colors (P, R, G, C); in the Two-Colors condition the points of each of the two 4-pointed components were colored, each component star having its own color. There were 6 different color combinations (PR, PG, PC, RG, RC, GC). Each of the color combinations had two variations, balancing the colors across the two 4-pointed component stars, and each of the colored stimuli alternated with one of the 4-pointed test outlines. As a result we obtained 4 x 2 x 2 = 16 unique One-Color trials and 6 x 2 x 2 = 24 unique Two-Colors trials. Note that for the One-Color condition there were 8 different color settings, accounting for the position of the colors with respect to the subsequent test outline; the four colors could lie inside the (subsequent) test outline (to be referred to as P_i, C_i, G_i, R_i) or they could lie outside the (subsequent) test outline (to be referred to as P_o, C_o, G_o, R_o). In a similar way, for the Two-Colors condition there were 12 different color settings, depending on the position of the colors with respect to the test outline (i.e., P_iR_o, P_iG_o, P_iC_o, R_iG_o, R_iC_o, R_iP_o, G_iC_o, G_iP_o, G_iR_o, C_iP_o, C_iR_o, C_iG_o). Repetition: All unique trials were shown twice, which revealed a total of 80 trials for each observer.

Procedure

During the experiment, a ring of 16 disks with colors taken from the Teufel & Wehrhahn color set was shown on the monitor screen. The actual stimulus was shown inside this ring (see Figure S1). Both the colored star configuration and the subsequent test outline were shown for 1000 ms, in an alternating fashion. The task of the participants was to judge the afterimage color in the center of the test outline. After viewing at least four cycles, the participants responded by selecting the colored disk that most resembled the perceived afterimage. The response was given by entering one of 17 keys on a keyboard (16 keys corresponding with one of 16 colors and one key was to be pressed when no afterimage was seen). The color disks were numbered 1 to 16 (see Supplementary Figure S1 for an example). Note that the colors numbered 1, 5, 9, 13 represent the colors P, R, G, and C, respectively.

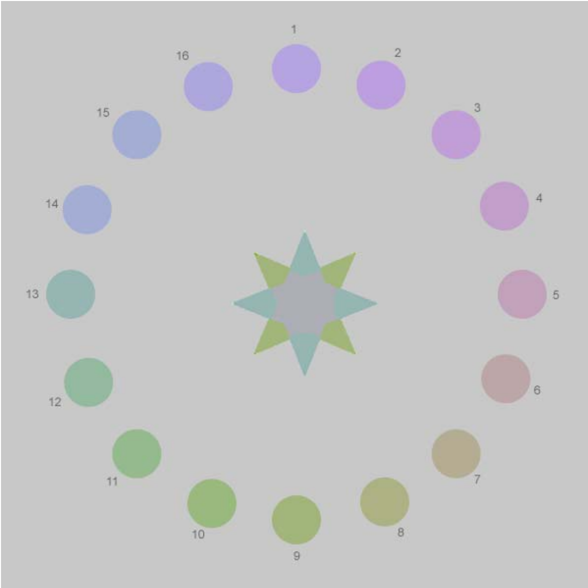


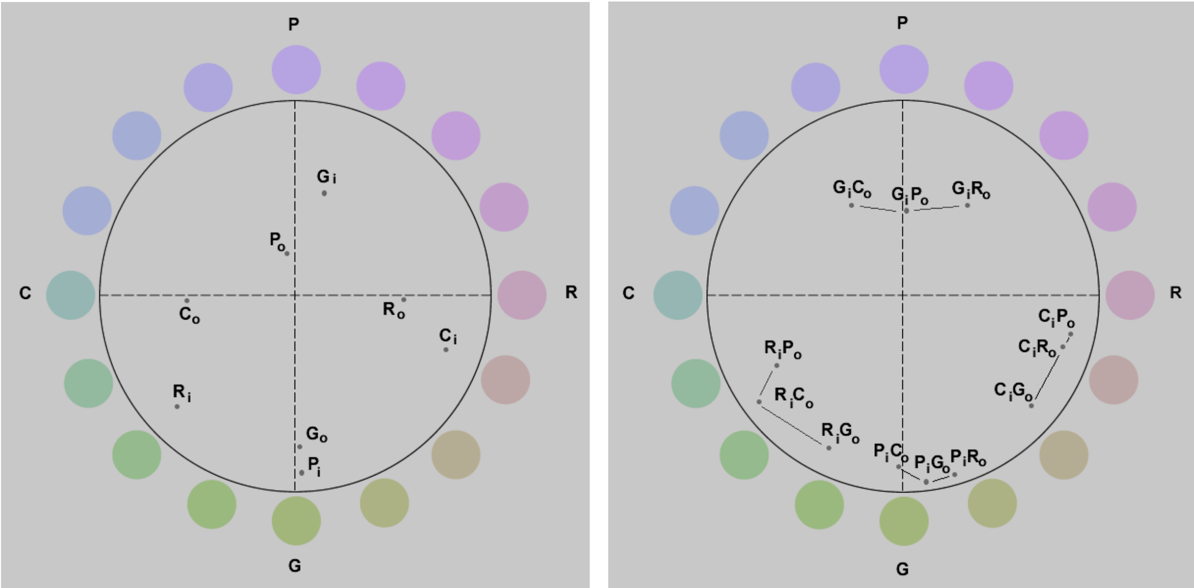
Figure S1. The stimulus was presented in the center of the screen and was positioned in the center of the Teufel-Wehrhahn color ring. The colored star stimulus alternated with one of two test outlines (not shown here) and the participants had to judge the color of the afterimage by selecting the color disk in the ring that resembled the afterimage color most. When no afterimage color was seen this could also be indicated.

Participants

Fifteen naive observers participated in the experiment (age 18-26 years). All participants had normal or corrected to normal vision and received course credits in turn for their participation.

Results

We have recoded each response in terms of coordinates on a circle with a radius of 1, matching with the position of the corresponding color disk (i.e., the response). The coordinates express the position on the Cyan-Red axis (x) and the Purple-Green axis (y). For example, the coordinates for the colors P, R, G and C are: P=(0,1), R=(1,0), G=(0,-1), C=(-1,0) etc. A no-afterimage response was recoded as (0,0). We then have calculated the mean afterimage coordinates for each color setting (based on 4 data points per participant per condition). In Figure S2A the afterimage coordinate plot is shown for the One-Color conditions when the colors were inside the subsequent test outline (i.e., One-Color inside condition, indicated by P_i, C_i, G_i, R_i) and when the colors were outside the subsequent test outline (i.e., One-Color outside condition, indicated by P_o, C_o, G_o, R_o). In addition, Figure S2B shows the plot for the Two-Colors condition.



A **B**

Figure S2. A) Mean responses for the One Color settings. The 16 color disks represent colors in the Teufel-Wehrhahn color ring. P, C, G, R are colors used in the stimuli (see text for CIE (x,y) values). All color judgments were recoded into coordinates, reflecting the position of the corresponding color disk on the circle (see text). The dots labeled P_i, C_i, G_i, R_i represent the mean responses on stimuli where the colors in the color stimulus were <u>inside</u> the subsequent test outline. The dots labeled P_o, C_o, G_o, R_o represent the mean responses on stimuli where the colors in color stimulus were <u>outside</u> the subsequent test outline. **B)** Mean responses on the Two Colors settings. The dots representing the mean responses on stimuli having the same inside color are connected with each other: (G_iC_o, G_iP_o, G_iR_o), (R_iP_o, R_iC_o, R_iG_o,), (P_iC_o, P_iG_o, P_iR_o), and (C_iP_o, C_iR_o, C_iG_o).

The plots in Figure S2A show that the afterimage colors for the One-Color condition go in different directions, depending on whether the color was inside or outside the subsequent test outline. The colors in the One-Color inside condition induced more or less complementary colors in the test outline, whereas the colors in the One-Color outside condition induced color appearances in the test outline that were similar to the presented colors (of course, all perceived afterimages were less saturated than the colors in the stimuli). The afterimages in the One-Color outside condition were the weakest: in 30% of the One-Color outside trials no afterimage was reported, whereas in 3.3% of the One-Color inside trials no afterimage was reported. The dominant influence of the colors inside the contours becomes especially clear when comparing the response coordinates on the Two-Color stimuli and the One-Color stimuli; the responses on the Two Color conditions appear to be more similar to corresponding One-Color inside conditions than to corresponding One-Color outside conditions. We have tested this by calculating the Euclidean distances between the response coordinates on the Two-Color condition and the corresponding response coordinates on the One-Color conditions (to be referred to with d_i and d_o, for the One-Color inside and One-Color outside conditions, respectively), for each observer (See Table S2). For all Two-Color responses, the mean distance with the corresponding One-Color-inside response was smaller than the mean distance with the One-Color-outside response, revealing an overall dominance of the afterimage of the color inside the contour (Paired samples T-test, t_{11}=-6.073, p=0.00081; the Shapiro-Wilk test revealed no deviation from normality). The mean ratio of the distances over all color settings was (d_i/d_o)= 0.44. In Table S2 the mean distances and the results on paired samples t-tests are given for each Two-Color condition (again, the Shapiro-Wilk test of Normality revealed no deviation from normality).

Although the colors outside the subsequent test outline induce relatively weak afterimages, they do have an effect. Consider the four clusters of response coordinates having the same inside color (G_iC_o, G_iP_o, G_iR_o), (R_iP_o, R_iC_o, R_iG_o), (P_iC_o, P_iG_o, P_iR_o), and (C_iP_o, C_iR_o, C_iG_o). Within each cluster, the response coordinates of the color settings having orthogonal colors (i.e., the first and last color settings in each cluster) differ from each other, such that the afterimage for each orthogonal pair shifts in the direction of the outside color ($G_iC_o \sim G_iR_o$: t_{14}= 6.137, p=000026; $R_iP_o \sim R_iG_o$: t_{14}= 5.042, p=0001710; $P_iC_o \sim P_iR_o$: t_{14}= 4.106, p=.001071; $C_iP_o \sim C_iG_o$: t_{14}= 6.647, p=.000011; for all distributions involved in these tests the Shapiro-Wilk test revealed no deviation from normality).

In conclusion, the current data reveal that a colored image may induce afterimage color filling-in within an outline presented after the image. Afterimages and filling-in are triggered and enhanced by the outlines. The afterimage color of a color outside the outline is similar to the inducing color (presumably resulting from contour enhanced contrast induction of the outside color afterimages) and is relatively weak, whereas the afterimage color of the color inside the outline is complementary to the inducing color and is relatively strong. When the colored image comprises colors that appear to be positioned inside and outside the subsequent outline, the afterimage colors tend to mix such that the afterimage color of the color inside the outline prevails.

Table S2

Mean d_i	Mean d_o	t_{14} (n=15)	p
(P_iR_o, P_i) = 0.282	(P_iR_o, R_o) = 0.994	-7.147	0.000005
(P_iG_o, P_i) = 0.201	(P_iG_o, G_o) = 0.267	-0.878	0.394790
(P_iC_o, P_i) = 0.223	(P_iC_o, C_o) = 1.001	-7.126	0.000005
(R_iG_o, R_i) = 0.393	(R_iG_o, G_o) = 0.560	-1.218	0.243532
(R_iC_o, R_i) = 0.211	(R_iC_o, C_o) = 0.623	-5.993	0.000032
(R_iP_o, R_i) = 0.389	(R_iP_o, P_o) = 0.966	-5.229	0.000128
(G_iC_o, G_i) = 0.497	(G_iC_o, C_o) = 0.946	-3.089	0.008010
(G_iP_o, G_i) = 0.407	(G_iP_o, P_o) = 0.721	-3.752	0.002146
(G_iR_o, G_i) = 0.435	(G_iR_o, R_o) = 0.819	-2.532	0.023944
(C_iP_o, C_i) = 0.250	(C_iP_o, P_o) = 0.993	-5.575	0.000068
(C_iR_o, C_i) = 0.200	(C_iR_o, C_o) = 0.531	-3.356	0.004709
(C_iG_o, C_i) = 0.485	(C_iG_o, G_o) = 0.591	-0.990	0.339118

Note: First, the Euclidian distance between the response coordinates on the Two Color stimuli and the response coordinates on corresponding One Color stimuli has been determined for each subject. For example: $d_i(P_iR_o, P_i) = (((P_iR_o)_x - (P_i)_x)^2 + ((P_iR_o)_y - (P_i)_y)^2\ )^{1/2}$ and $d_o(P_iR_o, P_o) = (((P_iR_o)_x - (P_o)_x)^2 + ((P_iR_o)_y - (P_o)_y)^2\ )^{1/2}$. Mean d_i, Mean d_o: the mean distance (across subjects; Euclidean distances between the response coordinates on the Two-Color condition and the corresponding response coordinates on the One-Color conditions); t_{14},p: results on a paired samples T-test.

Supplemental References

S1 Teufel, H.J., Wehrhahn, C. (2000). *J. Opt. Soc. America A* **17**, 994-1006.