Supplementary information

Separate experiments investigated how the rate of colour alternation influences (a) the effective chromatic contrast available to induce a McCollough effect and (b) visual awareness mechanisms. For (a), McCollough effect strength was measured first as a function of frame duration (Fig. 2a, Experiments 1 and 2), then as a function of chromatic contrast (not shown; Experiment 3: effect strength was nearly proportional to contrast). These two functions described how decreased frame duration (and thus increased colour alternation frequency) translates to decreased effective contrast in the stimulus inducing the after-effect (filled circles, Figure 2b). For (b), we measured the chromatic contrast required to directly perceive alternating colours at varying alternation rates (open circles, Figure 2b, Experiment 4). Figure 2b shows a steeper loss of sensitivity with increasing alternation frequency for conscious colour perception than for generation of the McCollough effect (Experiment 5 directly studies this difference in frequency response slopes).

Methods

Equipment and participants:

All experiments were conducted on University of California, San Diego undergraduates who provided written consent. Experiments were run on a Cambridge Research Systems VSG 2/5 board controlling a 21" IIyama Vision Master Pro 514 colour monitor. The monitor was set to a resolution of 1024x768 at a refresh rate of 100 Hz for Experiments 1-3, and to a resolution of 800x600 at a refresh rate of 160 Hz, for Experiments 4 and 5. The monitor was gamma corrected independently for each of these settings; phosphor persistence measurable with a photodiode lasted less than 4 msec.

Experiments 1 and 2

McCollough effect strength was measured with a nulling procedure. Subjects were exposed to 100 trials (about 6.33 min) of adaptation followed by 100 trials of counter-adaptation (where the colour-orientation pairings were switched). Each trial consisted of 3.8 s of a four-frame adaptation sequence (see Figure 1 c; gratings were roughly 1.82 cycles/degree filling the entire screen: roughly 36° in width, 27° in height; the CIE chromaticity coordinates for red and green were (0.6168, 0.3449) and (0.2696, 0.6130) respectively, their alternation yielding an L-cone modulation of 25% at a luminance of 16 cd/m^2) followed by a 300 ms presentation of the test field (Figure 1 b; about 15 degrees wide, presented on a black background). Subjects were asked to indicate which side of the test field "looked greener". Based on the subject's response, the chromaticity of the "whites" of the test stimulus was adjusted for the next trial to null the indicated after-effect colours while maintaining isoluminance at 45 cd/m^2. After about 50 trials, or about 3 minutes of adaptation, after-effect strength reached an asymptotic value.

For any given trial, the chromatic contrast (percent L-cone contrast) between the red-adapted and green-adapted sides of the test field was the measure of the momentary after-effect strength. The overall after-effect strength for a given frame duration was defined for each subject as the average momentary after-effect strength during the last 50 trials of the adaptation and counter-adaptation periods.

Experiment 1 used four different frame durations (10, 40, 160, and 960 ms; corresponding to colour alternation rates of 50, 12.5, 3.125, and 0.52 Hz) at maximum chromatic contrast of the adapting gratings. McCollough effect strengths were significantly greater than zero for all alternation rates (50 Hz: $t(9)=3.2$, $p<0.05$; 12.5 Hz: $t(9)=6.3$, $p<0.001$; 3.125 Hz: $t(9)=9.5$, $p<0.0001$; $t(9)=7.7$, $p<0.0001$).

Experiment 2 was conducted on 5 of the 10 subjects from Experiment 1 to verify the finding of a significant McCollough effect at 50 Hz colour alternation. We independently measured McCollough effect strength for frame durations of 10 and 20 ms (colour alternation rates of 50 and 25 Hz) twice for each subject. Again, the after-effect was significant at both frame rates (50 Hz: $t(9)=2.3$, $p<0.05$; 25 Hz: $t(9)=7.5$, $p<0.0001$).

Experiment 3

To find the strength of the McCollough effect as a function of chromatic contrast in the inducing gratings, Experiment 3 manipulated chromatic contrasts of the inducing stimuli to be one of four values: 3.17%, 6.34%, 12.68%, and 25.36% (L-cone contrast) all presented at 960 ms per frame. After-effect strength was roughly proportional with inducing contrasts (for our stimuli, mean after-effect strengths were 0.24, 0.65, 1.06, and 1.79% L-cone contrast, respectively; that is, about 7.5% of inducing L-cone contrast).

Experiment 4

To measure the degree to which increasing frequency of colour alternation decreased the effective chromatic contrast available to visual awareness, we used a standard Yes/No detection staircase on isoluminant chromatic flicker. The red-green isoluminance ratio was set for each subject using a minimum motion procedure[17]. Using this ratio, we could manipulate L-cone modulation without altering the luminance. Eight frame durations were used (25, 31.25, 37.5, 43.75, 50, 62.5, 100, 250, and 500 ms, a range suggested by previous research[11, 12], corresponding to colour alternation rates of 16, 13.3, 11.43, 10, 8, 5, 2, 1, and 0.5 Hz).

Subjects were presented with a flickering two frame sequence and indicated whether or not they could “see both red and green”. If the colours were seen, the chromatic contrast for the next trial at that frame duration was decreased, if the colours

were not seen, the chromatic contrast was increased. Frequency of seeing curves were fit to the response patterns of each subject at each alternation frequency, and 50% thresholds were estimated. Relative sensitivity (1/threshold) from this experiment is plotted in Figure 2 b. While only the uniform field flicker results are reported here, we also measured chromatic sensitivity to a flickering field with uniform black bars (simulating McCollough effect conditions); the bars simply made the detection task uniformly more difficult, increasing the threshold contrast by approximately 30%.

Experiment 5

The purpose of Experiment 5 was to quantitatively demonstrate the difference in slopes observed in the previous experiments. We measured chromatic modulation sensitivity (as in Experiment 4) and McCollough effect strength (as in Experiments 1-3), in 14 subjects at color alternation rates of 6.7 and 13.3 Hz. The slope for each of the perception tasks was defined as either the proportion of color contrast sensitivity or proportion of McCollough effect strength at 6.7 Hz, that was measured at 13.3 Hz. The difference in slopes was indeed significant ($t(13)=2.89$; $p<0.05$), with color contrast sensitivity at 13.3 Hz equal to 0.45 of the sensitivity at 6.7 Hz, and McCollough effect strength only being reduced to 0.65 of the 6.7 Hz strength.