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The McCollough World: Induction of orientation-contingent aftereffects with an altered-reality system

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ABSTRACT

The McCollough Effect is a color aftereffect produced by exposure to colored, oriented patterns. For example, following adaptation to vertical red and horizontal green stripes in alternation, vertical black and white patterns appear greenish, while horizontal black and white patterns appear reddish. The striking aspect of the McCollough Effect is that just a few minutes of adaptation can produce an aftereffect lasting days or weeks. Though this effect is easily induced, previous work has shown that stronger effects can be achieved with longer periods of adaptation. To allow especially long adaptation durations, the current work develops a novel method of induction of the McCollough Effect using live video feed, filtered by orientation, and viewed with a head-mounted display. Results showed that this "McCollough World" paradigm was as strong an inducer (per unit time) as traditional paradigms using gratings, while allowing observers to adapt comfortably for multiple hours. Two hours of McCollough World adaptation produced effects that were significantly larger than 20 min of traditional adaptation, which is close to the tolerance limits for gratings. This work provides insight into the features necessary for induction of the McCollough Effect and provides a strategy for creating especially strong and long-lasting color aftereffects.

1. Introduction

The McCollough Effect (ME) is a well-known visual illusion characterized by long-lasting color aftereffects following adaptation to two color/orientation pairings (McCollough, 1965). For example, viewing a red and black vertical grating alternating with a green and black horizontal grating causes achromatic vertical and horizontal patterns to appear greenish and reddish, respectively. Among aftereffects, the ME is notable in that it is very long-lasting, with some hypothesizing that aftereffects are nearly permanent (Jones & Holding, 1975; Vul, Krizay, & MacLeod, 2008). Because of this, the ME has been widely studied since its inception (for reviews see Howard & Webster, 2011; Stromeyer, 1978). Despite the large amount of work on the ME, its neural locus and underlying mechanisms remain an open question.

Mindful of addressing these long-standing mysteries, the goal of this work was to create a strong, long-lasting ME that could be amenable to study in future behavioral and neuroimaging work. Though the ME can be induced with only a few minutes of exposure, previous studies have shown that longer periods of adaptation to ME stimuli result in stronger adaptation effects (Riggs, White, & Eimas, 1974; Vul et al., 2008). Following this logic, a very strong ME, ideal for physiological study, should in principle be achievable by adapting participants for multiple hours. However, participants often find the experience of adapting to high-contrast gratings uncomfortable and visually exhausting (Conlon et al., 1998).

In order to overcome this roadblock, the current work describes a novel method for inducing the McCollough Effect using an "altered-reality" system to create a more comfortable and engaging adaptation paradigm. Our method used a head-mounted display (HMD) with an attached camera to filter a live-feed of the participant's environment. Similar techniques have been used to study long-term orientation deprivation (Engel, Zhang, Bao, Kwon, & He, 2009; Haak, Fast, Bao, Lee, & Engel, 2014). Using altered-reality lays the groundwork for doing potentially a day-long study with even stronger effects, enabled by allowing participants to perform some normal daily tasks while adapting. This would not be possible with a monitor.

The purpose of this study was to 1) determine if we could effectively induce a McCollough Effect in an altered-reality system that could be worn comfortably for multiple hours, and 2) to ensure that this effect was at least comparable in strength to the classic method of inducing the

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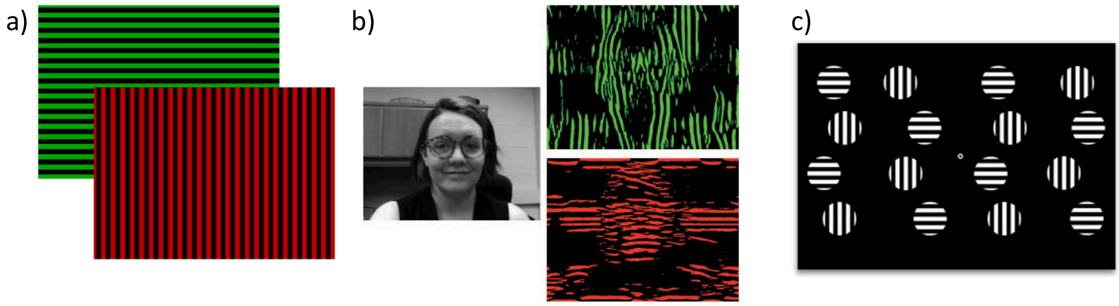

Fig. 1. Examples of stimuli. All were displayed on the HMD. a) Classic ME inducing stimuli. b) Examples of McCollough World inducing stimuli and filtering. Input for McCollough World were processed from the attached camera. c) Hue cancelation test display; the identical configuration was used for both adaptation paradigms.

McCollough Effect. While wearing the altered-reality system, incoming images from the external camera were filtered in the Fourier domain to limit energy to a narrow band of either vertical or horizontal orientations, then binarized to make defined, high-contrast edges. This filtering made the entire altered-reality environment appear striped. We then paired high contrast red and green to the vertical and horizontal stripes and alternated the video feed between color/orientation pairings every two seconds. Participants watched videos in this "McCollough World" environment for two hours with periodic tests to determine the strength of the built-up aftereffect. We tested the McCollough World paradigm against a "classic" version of the McCollough Effect, where participants adapted to simple square-wave gratings with similar spatial and color properties, within the same HMD. We showed that the McCollough World paradigm was effective and subjectively more comfortable than the classic paradigm and used it to produce larger and longer-lasting aftereffects than 20 min of traditional adaptation, about the tolerance limit for viewing bright gratings. We also analyzed potential differences in adaptation between the two techniques, providing insight into essential aspects of ME induction.

2. Methods

2.1. Participants

16 participants (10 female, ages 19–31) completed two adaptation sessions. All had normal or corrected-to-normal vision. Individuals who reported VR-related discomfort or VR sickness were excluded. All experimental protocols were approved by the University of Minnesota Institutional Review Board, and participants provided written consent prior to the start of the experiment.

2.2. Stimuli

All stimuli (including all test patterns and both McCollough World and Classic McCollough Effect adapters) were presented in a head-mounted display (nVisor SX LCOS display, 1280 by 1024 pixels) with an attached camera (UI-1220-M 640 × 480 × 8 bits@30 Hz) connected to a Dell XPS M1730 laptop with dual NVIDIA 8800 m GTX graphic processing units. Stimuli were generated using the Psychophysics Toolbox (Brainard, 1997) for MATLAB (MathWorks). The visual field was ~40 × 30 degrees of visual angle. In order to achieve reasonably high luminance contrast and to be consistent with previous work, the red/black gratings were generated using the red pixel value at 100 percent, and the green/black grating used the green pixel value at 100 percent.

2.2.1. Classic McCollough Effect

The classic McCollough Effect was induced using full-screen, static square-wave gratings with 1.6 cycles/degree (Fig. 1a), alternating in orientation (horizontal or vertical) and between green/black and red/black gratings every 2 sec. As noted above, these inducing stimuli were presented on the HMD.

2.2.2. McCollough World

To create the "McCollough World," participants viewed videos through the HMD with an attached camera. Participants viewed videos of their choice (usually on Netflix), but the filter seemed to work best with live-action videos and videos with brighter lighting; thus, participants were encouraged to select videos with these characteristics. Videos were presented on an external display, and participants positioned themselves such that the entire scene was visible with the HMD's attached camera. Incoming frames from the camera were filtered in the Fourier domain with a Butterworth filter to limit energy to a narrow band of orientations and then were binarized (Fig. 1b). Vertical and horizontal filters were paired with red and green, and the color/orientation pairs alternated every 2 sec. The McCollough World images were roughly matched in spatial frequency to the classic ME (~1.6 cycles/deg.) but varied across the scene depending on the spatial frequency content of the scene being filtered.

2.2.3. Hue cancelation task

To measure the magnitude of the aftereffects, participants were shown an array of horizontal and vertical square-wave gratings (Fig. 1c) and asked to adjust the color of the gratings until the stimulus appeared achromatic. To cancel hues induced by the ME, participants added the adapting color to the stimulus in order to cancel out the color aftereffect. For example, adapting to a red-vertical pairing will cause vertical, physically achromatic gratings to appear green, and red must be added to cancel the illusory color. The amount of color needed to make the gratings appear achromatic (gray or white) served as a measure of aftereffect strength.

The color contrast of the test grating patches was randomized at the start of every trial. Contrast was presented in nominal units of threshold, from a modified version of the MacLeod-Boynton color space (Derrington, Krauskopf, & Lennie, 1984; Krauskopf, Williams, & Heeley, 1982; Macleod & Boynton, 1979), with contrast scaled to be in units of approximate detection threshold (Webster, Miyahara, Malkoc, & Raker, 2000). Button presses increased distance from the origin (Illuminant C) of the colored stripes along the L vs M 'cardinal' axis, changing color contrast but keeping luminance and hue direction constant. Step sizes of color contrast were one threshold unit. Horizontal and vertical gratings were adjusted simultaneously, meaning moving one in the + L direction (more reddish) moved the other in the -L direction (more greenish).

Pilot testing was used to confirm that the hues presented adequately canceled out the aftereffects. In a classical afterimage paradigm, it would be expected that participants would not be able to fully cancel out the afterimages with values restricted to the primary axis of a cone-opponent space (L vs M here) since the red and green pixel coordinates that defined the inducer were not aligned with that axis. However, when early participants were given the option to freely adjust

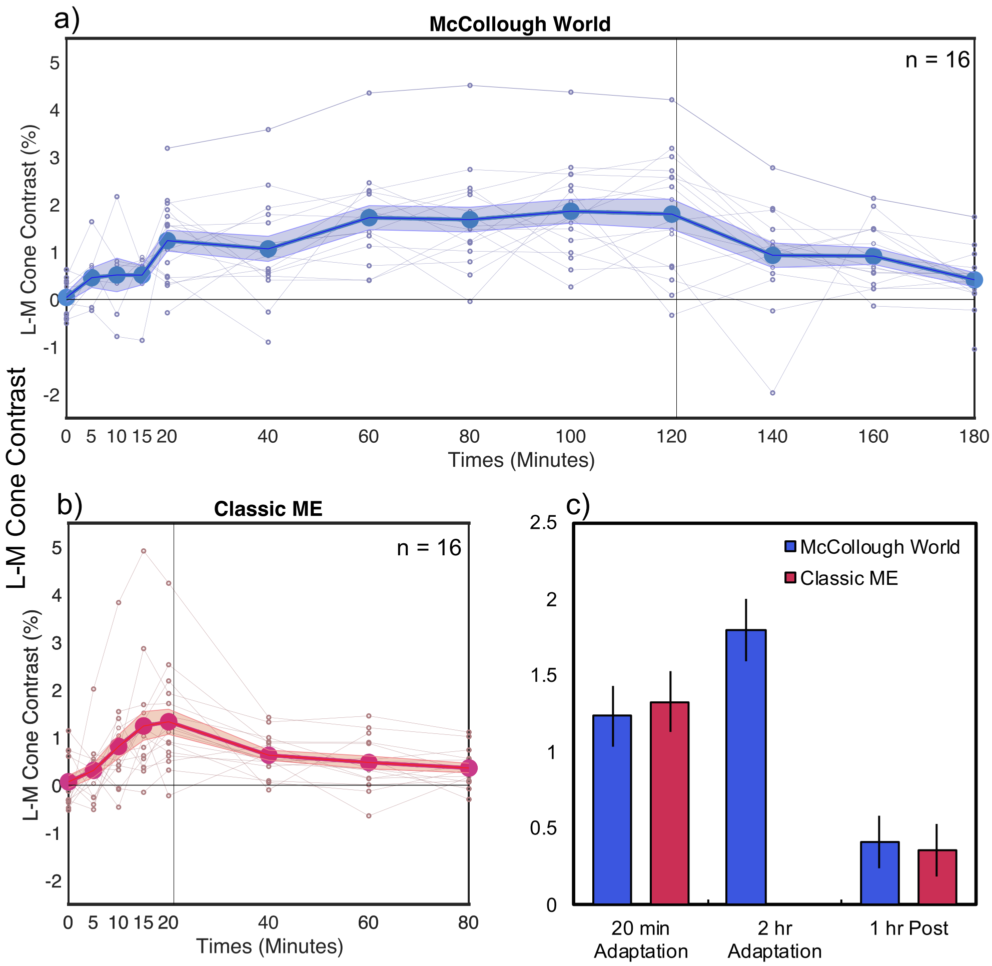

Fig. 2. The adaptation time course of the hue cancelation task for the McCollough World (a), and the classic McCollough Effect (b), where means are shown in large circles, individual data are shown in smaller points, and shaded areas are standard error of the mean. c) Mean hue cancelation results at 20 min of adaptation, the peak of adaptation (1 h for McCollough World and 20 min for Classic ME), and 1 h post-adaptation. Black bars represent ±1 standard error of the mean difference between conditions, which is appropriate given our within-subjects design.

stimuli in arbitrary direction in cone-opponent space after induction of the ME, participants did not consistently add contrast along the S vs LM axis. This is in agreement with previous work that showed a bias toward red and green afterimages when the ME was induced with a variety of colors (Stromeyer, 1969).

Participants finalized their settings with a button press when their adjustment appeared sufficiently achromatic. Each hue cancelation test lasted for 1 min, with participants generally completing 3 to 5 settings per test. All tests took place inside the HMD, with a keyboard placed in the participant's lap. Participants practiced this task for 10 to 20 min at the start of their first session, until they could perform the task quickly and consistently. Most participants found the task to be easy and intuitive.

2.3. Procedure

All participants completed 20 min of adaptation to the classic McCollough Effect paradigm (alternating square-wave gratings), and 2 h of adaptation to the orientation-filtered "McCollough World." The two paradigms were completed in sessions on different days, separated by at least 24 h. The order of the two sessions was counterbalanced, as was the color/orientation pairing for each session (e.g. green/vertical and red/horizontal or red/vertical and green/horizontal).

Throughout each adaptation session, participants performed the hue cancelation task, locking in as many achromatic settings as possible in 1-minute blocks. During the 20-minute classic ME session, tests were given every 5 min. For the first 8 participants, tests were given every 20 min during the 2-hour McCollough World session. For the next 8, participants were additionally tested every 5 min during the initial 20-minute period, and then every 20 min for the remaining 1 h 40 min. In both sessions, participants performed 3 additional blocks of the task following removal of the adapter, every 20 min for 1 h, in order to track the decay of adaptation.

Results are plotted in L-M cone contrast calculated using Smith & Pokorny (1975) cone fundamentals:

$$L_{contrast} = (L1 - L2)/(L1 + L2)$$

$$M_{contrast} = (M1 - M2)/(M1 + M2)$$

where L1 is the L cone value needed to cancel the green aftereffect, L2 is the cone value needed to cancel the red aftereffect, $M1 = 1 - L1$, and $M2 = 1 - L2$. Plotted values are $L_{contrast} - M_{contrast}$.

3. Results

Plotting our results reveals that the McCollough World paradigm was effective in producing strong aftereffects. Fig. 2a shows results with our new method, where participants adapted for 2 h to narrowband orientation-filtered videos, also reversing between red and green and horizontal and vertical. For comparison, Fig. 2b shows results for the classic McCollough effect experiment, where participants adapted to static gratings, alternating between red and green and horizontal and vertical for 20 min. For both methods, participants completed hue cancelation tasks during the adaptation period, and at 20 min. intervals for 1 h post-adaptation.

One-sample t-tests revealed that there was a significant adaptation effect vs baseline after 20 min of adaptation to the McCollough World ($t = 5.64$, $p = 0.0002$), 20 min of adaptation to the classic ME ($t = 5.05$, p

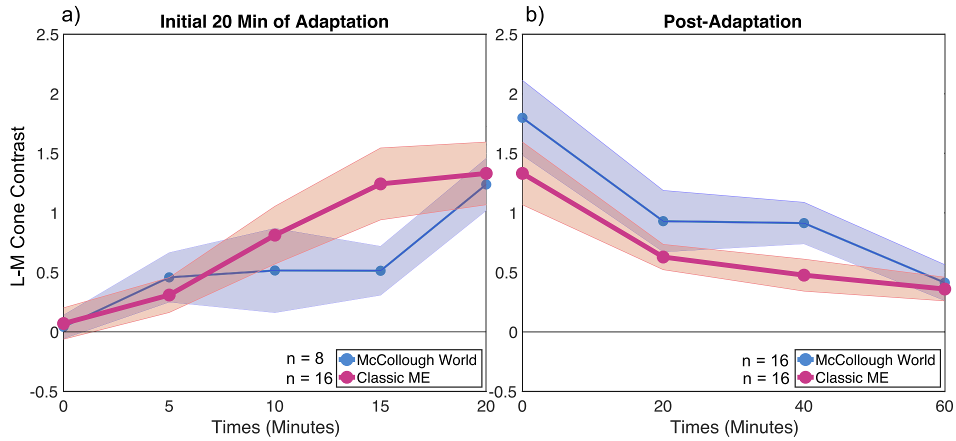

Fig. 3. The initial 20 min of adaptation (a) and 1 h of post-adaptation (b) for the Classic ME (red), and the McCollough World (blue), shaded areas around each line are the standard error of the mean within-subject differences.

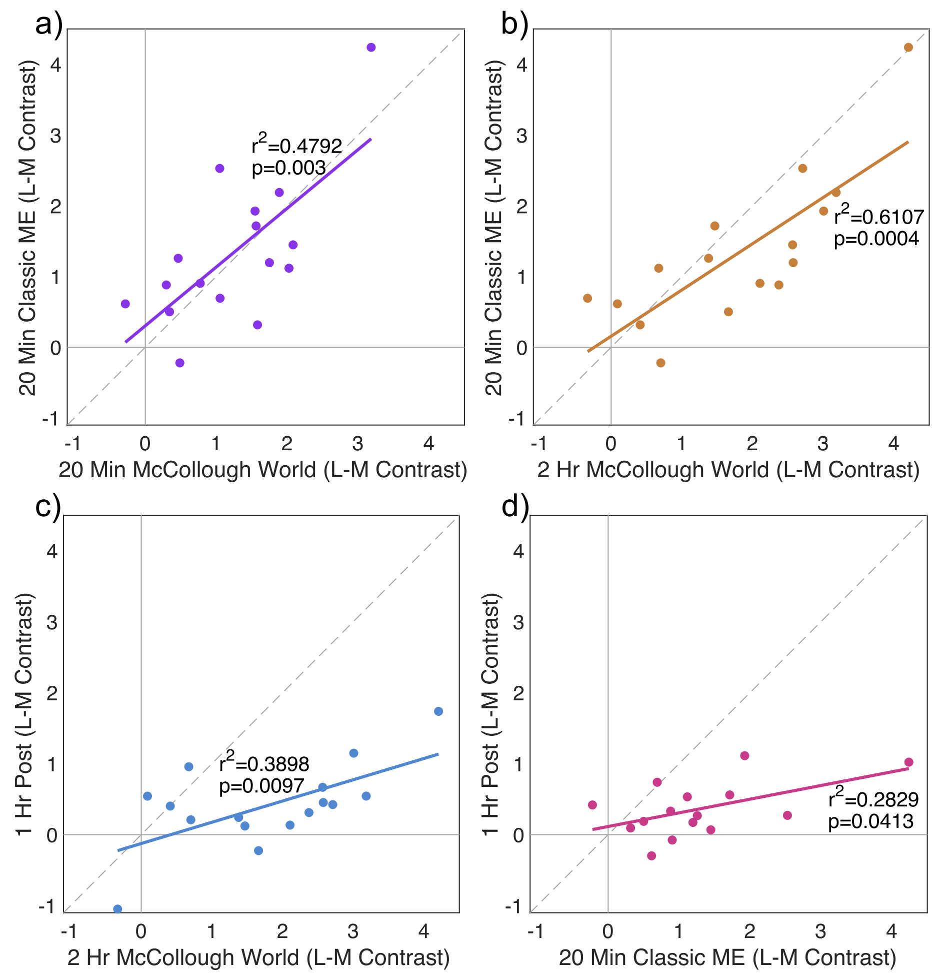

Fig. 4. Individual observer results plotted for a) the Classic ME paradigm, against the McCollough World paradigm for 20 min. of adaptation (purple) b) 20 min. of the classic ME vs 2 h of the McCollough World (orange). c) The 2 h of adaptation in the McCollough World vs 1-hr post-adaptation (blue). d) 20 min. of adaptation to the classic ME vs 1 h post-adaptation (red). Lines represent a linear fit to the data, and numbers are Pearson correlations.

= 0.0004), and 2 h of adaptation to the McCollough World ($t = 5.71$, $p = 0.0002$). A one-sample t-test also showed that the effect persisted 1-hour post-adaptation for both the McCollough World ($t = 2.74$, $p = 0.02$) and the classic ME ($t = 3.62$, $p = 0.006$).

We also performed paired t-tests to compare the strength of the effects across the two paradigms (see Fig. 2c, paired tests are possible because of our within subjects design). We found that our new method was at least as effective as the classic method at 20 min, as the two were not significantly different ($t = -0.48$, $p = 0.73$). Additionally, we found that 2 h of adaptation in the McCollough World resulted in significantly larger adaptation effects than the 20 min of classic adaptation ($t = 2.38$, $p = 0.04$). Surprisingly, there was no difference in adaptation between the two methods 1 h post-adaptation despite the longer adaptation time for the McCollough World ($t = 0.79$, $p = 0.28$). All p-values were corrected for multiple comparisons using Benjamini & Hochberg's method of False Discovery Rate (Benjamini & Hochberg, 1995).

Fig. 3a shows the rise of the adaptation effect during the first 20 min of adaptation. Adaptation for the two effects showed similar dynamics during this period. Fig. 3b shows the decay over 1-hour post-adaptation. The slope of the decay was also similar for the two adaptation effects.

We also computed Pearson correlations to determine if the afterimage induced in one adaptation paradigm was predictive of the degree of adaptation in the other. We were interested in whether participants differ in their susceptibility to the ME regardless of the induction method. We found significant correlations for the two measures of adaptation build-up: Fig. 4a shows individual results for Classic ME and McCollough World plotted against each other at 20 min of adaptation ($r^2 = 0.4792$, $p = 0.003$), and Fig. 4b shows 20 min. of the classic methods plotted against 2 h. in the McCollough World ($r^2 = 0.6107$, $p = 0.0004$). Correlations also confirmed the finding that larger effects at the end of the adapting period result in larger long-lasting aftereffects: the size of the adaptation effect for each method was significantly correlated with the size of the effect that persisted 1 h post-adaptation (McCollough World $r^2 = 0.3898$, $p = 0.0097$, and Classic ME $r^2 = 0.2829$, $p = 0.0413$, see Fig. 4c and d).

4. Discussion

Using our McCollough World paradigm, participants were able to adapt for two hours in a single session and achieve orientation-contingent aftereffects that grew at a rate comparable to that of traditional methods (Classic ME). Verbal reports of participants indicated that they found the McCollough World paradigm comfortable, suggesting that it is promising for long-duration studies.

We compared the strength of adaptation from 2 h in the McCollough World to a classic 20 min ME induction paradigm (about the tolerance limit of viewing square wave gratings). As measured by the hue cancelation task, the McCollough World produced stronger aftereffects than the traditional paradigm (Fig. 3). Effects from both paradigms were, long-lasting; on average, participants still showed highly reliable aftereffects 1 h later.

We also found that the overall strength of the McCollough Effect varied a great deal across participants, and that the strength of the adaptation effect for each participant was significantly correlated across the two induction methods (Fig. 4a and b). This suggests that methods tap into similar underlying mechanisms, and that these mechanisms vary in strength reliably across observers (Mollon, Bosten, Peterzell, & Webster, 2017). Additionally, within each method the strength of the effect 1 h after adaptation was significantly correlated with the overall degree of adaptation (Fig. 4c and d). This is consistent with previous work showing that the strength of the ME is linearly correlated with the decay (Riggs et al., 1974), providing further support that the McCollough World is inducing a classically defined McCollough Effect.

Interestingly, some participants also informally reported "real-world" aftereffects following the McCollough World induction, wherein vertical and horizontal edges of objects they viewed outside the AR-headset appeared to have hue (ex. door frames and keyboards). These color fringes seemed to last less than 20 min as most who reported the real-world color fringes reported that they were gone prior to the first post-adapt test. The experience of real-world color aftereffects may speak to the generalizability of the McCollough World method. Previous research has shown that the ME is spatial frequency and orientation specific (Ellis, 1976, 1977; Fidell, 1970; Lovegrove & Over, 1972; Stromeyer, 1972). The filter used in our McCollough World paradigm was fairly narrow, but scenes still contained minor variations in both of these visual categories, suggesting that the McCollough Effect is robust to scenes with minor spatial and orientation variations. It is potentially the slight variability in scene statistics that allowed the McCollough Effect to generalize to edges in the real world.

A potential drawback of this study is that we did not measure variations in attention, due to fatigue or discomfort that could have potentially differed between methods, and so produced differences in the strength of adaptation. Inattention may not be a large contributing factor to the difference between the two methods, however, as previous work has shown that the ME is invariant to changes in attention (Houck & Hoffman, 1986).

In summary, we have shown that strong and long-lasting McCollough effects can be generated using multiple hours of adaptation to a "McCollough World." Future work will examine induction durations even longer than 2 h. Aftereffects produced in this way should be ideal for use in physiological studies, where strong effects should be produced from large changes in neural response, measurable with fMRI, EEG, and other methods.

Credit authorship contribution statement

Katherine E.M. Tregillus: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing - original draft. **Stephen A. Engel:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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