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When Red Lights Look Yellow

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Purpose. Red signals are typically used to signify danger. This study was conducted to investigate a situation identified by train drivers in which red signals appear yellow when viewed at long distances (~900 m) through progressive-addition lenses.

Methods. A laboratory study was conducted to investigate the effects of defocus, target size, ambient illumination, and surround characteristics on the extent of the color misperception of train signals by nine visually normal participants. The data from the laboratory study were validated in a field study by measuring the amounts of defocus and the distances at which the misperception of the color of train signals was apparent and whether these distances varied as a function of time of day.

Results. The laboratory study demonstrated that small red targets (~1 min arc) can appear yellow when viewed through small amounts of defocus (~ +0.75 D) under bright illumination (1910 cd/m^2). In the field study, the defocus needed to produce the color misperception was similar to that found in the laboratory study. Time of day affected the color misperception, and there was no misperception at night.

Conclusions. The color misperception is not solely associated with progressive-addition lenses, but occurs in the presence of small amounts of positive defocus. The potential for the misperception to result in collisions and fatalities presents a major safety concern. (*Invest Ophthalmol Vis Sci.* 2005;46: 4348–4352) DOI:10.1167/iovs.04-1513

A train driver reported that some red warning train signals appeared yellow when viewed through his progressive-addition lenses, but not when viewed through his bifocals. This phenomenon was reported at long distances, typically 600 to 900 m, where the signals subtended less than 1 min arc. Such observations are of concern, given that the braking response to yellow signals is quite different from the response to a red signal and could result in a "signal passed at danger." This is particularly significant, given that progressive-addition lenses are used by 35% to 40% of presbyopes in Australia (information provided by Sola International Holdings), and the mean age of train drivers is increasing.

A site visit confirmed the train driver's observations and permitted documentation of the conditions under which the color misperceptions occurred. Red signals appeared yellow when the driver viewed either incandescent or light-emitting diode (LED) train signals through the top of the lens corridor of the progressive lenses, but the color misperception was also noted through lenses of fixed positive defocus relative to the observer's distance spectacle prescription. It did not occur with lens powers in excess of +1.00 D, as the signals became too blurred for the viewer to distinguish the color. A comprehensive eye and vision examination of the train driver who had originally reported the color misperception revealed that his corrected vision was normal. The train driver was also shown to have normal color vision, as assessed by the Ishihara, Farnsworth Lantern, and Farnsworth D15 tests. His progressive-addition spectacles, but not his bifocals, were blurred in the distance portion by approximately +0.50 D.

The purpose of experiment 1 was to investigate the signal color misperception in the laboratory by simulating the field conditions under which it was reported. We validated the data under field conditions in experiment 2, by measuring the amounts of defocus and distances at which the misperception of the color of train signals was apparent in the field, and we determined whether the data varied as a function of time of day.

Methods

Experiment 1

Light signals were constructed based on the spectral properties of railway warning signals (see Fig. 1). Figure 2 shows the experimental setup. Simulated single-aspect train lights of four different signals: bright red (luminance 11,300 cd/m^2 Commission Internationale de l'Éclairage [CIE] chromaticity coordinates 0.69, 0.31), dark red (5,460 cd/m^2, 0.69, 0.31), bright yellow (35,000 cd/m^2, 0.58, 0.42), and dark yellow (17,400 cd/m^2, 0.58, 0.42) were displayed for 5 seconds. A black circular disc with a 2-mm aperture was mounted in front of the lights, to produce signals that subtended 1.38 minutes and 0.69 minutes at 5 and 10 m, respectively. The white surround contained a 6-mm aperture, through which both the 2-mm signal and the black surround (produced by the circular disc) could be viewed and that simulated the railway practice of using shields around signals.

An auxiliary projector was used to simulate the effects of the bright, sunlit conditions in the field under which the color misperception was most noticeable. The projector produced an illuminated region (642 × 575 mm) surrounding the signals, but was angled so that it did not illuminate them directly. The luminance of the white surround was 100 and 1910 cd/m^2 with the projector turned off and on, respectively.

Nine volunteers (five men, four women) with normal visual acuity (6/6 or better) and normal color vision, as measured with the Ishihara test, participated in the experiments (mean age, 30.7 ± 10.8 years, range 20–49). The study was conducted in accordance with the requirements of the Queensland University of Technology Human Research Ethics Committee and adhered to the tenets of the Declaration of Helsinki. All participants were given a full explanation of the experimental procedures and written informed consent was obtained, with the option to withdraw from the study at any time. Observers were instructed to report whether the signal color was either red or more orange/yellow. If the color of the light seemed to be between, the observers were instructed to report whether it appeared closest to red or to orange/yellow. Observers were also asked to indicate whether the light was too dim to see. Testing was conducted monocularly, with the nontested eye occluded.

For each observer, the lenses required to produce four levels of defocus (0.00 D, +0.50 D, +0.75 D, and +1.00 D) were determined. A set of conditions consisted of six presentations at each defocus level for each of the four signals (96 presentations) presented in random

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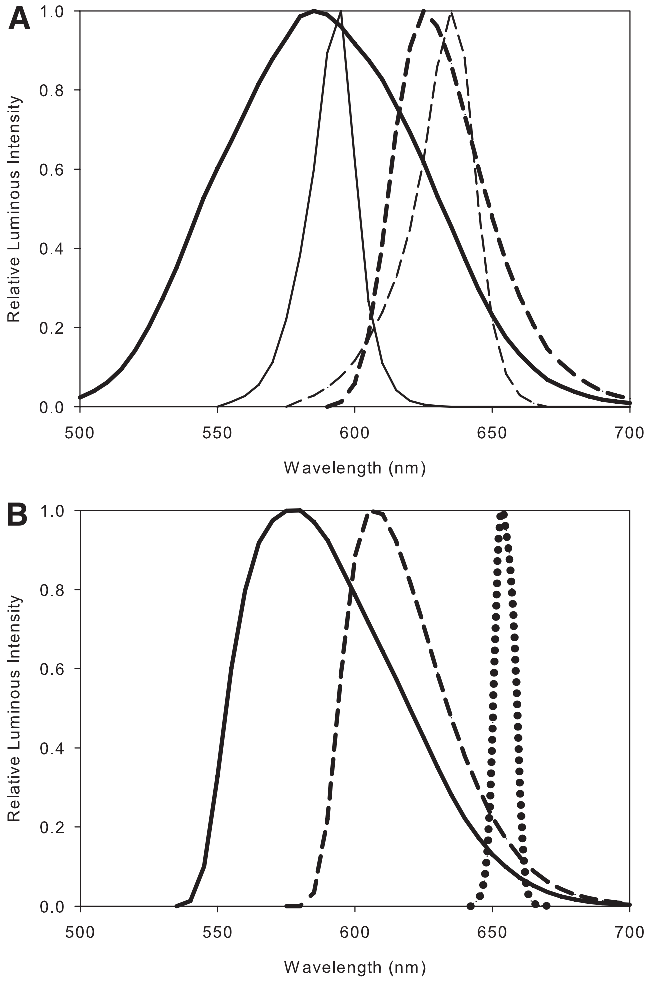

FIGURE 1. Normalized spectral luminous intensities of red and yellow signals in (**A**) railway signals measured in the laboratory: yellow incandescent (*thick solid line*), yellow LED (*fine solid line*), red incandescent (*thick dashed line*), and red LED (*fine dashed line*) and in (**B**) experiment 1: yellow signal (*solid line*), red signal (*dashed line*) and narrow-band red signal (*dotted line*). The CIE chromaticity coordinates of the railway signals are yellow incandescent (0.57, 0.43), yellow LED (0.58, 0.42), red incandescent (0.72, 0.28), and red LED (0.71, 0.29). The CIE chromaticity coordinates of the signals in experiment 1 are given in the Methods section.

order. There were four sets of conditions: two testing distances (5 and 10 m, equivalent to 500 m and 1 km in the field) and two surround illumination conditions (auxiliary projector off and on, corresponding to 100 and 1910 cd/m^2).

Dynamic measurements were also made at 10 m with the auxiliary projector turned on to determine how much additional positive power was needed to distinguish any color change in the appearance of the bright red signal. The measurements were made initially with trial progressive-addition lenses and then with an Alvarez lens, which allows lens power to be gradually manipulated in either the positive or negative direction.[1,2] An Alvarez lens consists of two lenses placed in close proximity to each other, where the thickness of each lens follows a cubic function. When aligned with each other at any point, the two lenses have equal and opposite power.

The effect of changing the extent and contrast of the surround was determined at the testing distance of 10 m, with the auxiliary source illuminated and with +0.75 D of defocus (as these were the conditions in which the strongest color misperception of the red signal occurred in pilot investigations). The annular backgrounds included a series of different diameter matt-black backgrounds including a 12-mm diameter (1.2-m equivalent at 1 km), 18-mm diameter (1.8-m equivalent), 22-mm diameter (2.2-m equivalent), and 50-mm diameter (5.0-m equivalent) background. Without the annular backgrounds, two additional large-diameter surrounds (297 × 210 mm) replaced the white background. These were light gray (54% relative reflectance) and dark gray (19.7% relative reflectance). The backgrounds were placed in a random order around the aperture where the signal light was presented, and the instructions to the observers were the same as for the previous parts of the experiment.

For one observer (JMW), accommodation was paralyzed, and the study was repeated, for accurate investigation of both negative and positive defocus power on the extent of the color misperception of the red signal.

A further part of this experiment was to determine for three observers whether the color misperception still occurred when the spectral characteristics of the red target were manipulated to consist of only a very narrow band of long wavelengths. A narrow-band red interference filter (570 cd/m^2, dominant wavelength 654 nm, chromaticity coordinates 0.73, 0.27; see Fig. 1B) was positioned in front of the halogen light source (replacing the original chromatic and 0.3 neutral density [ND] filters) and the experimental procedures repeated with the Alvarez lens to produce both positive and negative defocus dynamically.

Experiment 2

Three sites at which the color misperception had been previously reported were selected to quantify some of the observations made in the laboratory. The latitude of the sites was 23°, 51 minutes south and the observations were made in mid May (late autumn/fall). At each of the three sites, the train signals were viewed at a series of distances along the train line (900–300 m) in 50-m steps through small amounts of defocus, which could be manipulated on a continuous scale and estimated to the nearest 0.25 mm (0.06 D) using an Alvarez lens system. Data were collected for two observers (JMW, DAA).

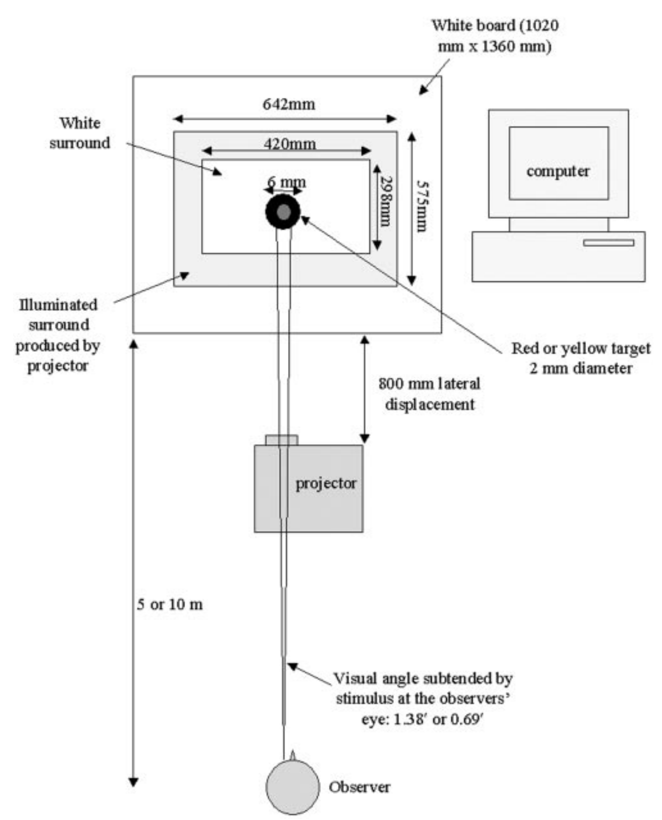

FIGURE 2. Schematic representation of experiment 1.

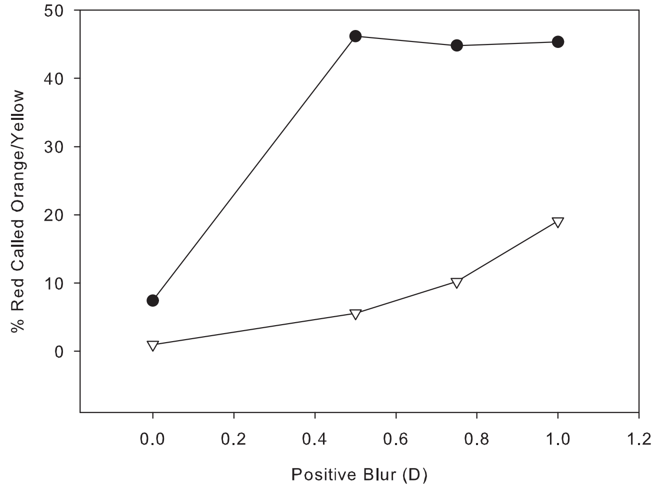

Figure 3. Group mean data (±SE) in experiment 1 for the percentage of target presentations in which observers miscalled a red signal as orange/yellow, as a function of positive defocus at 5 m (△) and 10 m (●) testing distances, in the presence of the auxiliary illumination source.

The distances at which the color misperception was observed were recorded with two single-frequency handheld GPS (12XL; Garmin Asia, Shijr, Taiwan) receivers. Two receivers were used for comparison and reliability. Before measurement of color misperception, we recorded the coordinates of the GPS receiver when positioned directly beside each of the train signals of interest. These coordinates were stored within the receiver and referred to as way points. By using the tracking mode of the GPS receivers, the user was able to move away from the way point (i.e., the position of the train signal), with the GPS receiver constantly updating its own coordinates and recording the distances (±10 m) from the way point that had been previously stored. The times of day at which the signals were viewed were also recorded, to calculate the direction of the sun relative to the signals and the observers and also the altitude of the sun.

It was not practical to measure the luminances and chromaticities of the train signals in the field trials because of insufficient time (we had to visit three sites within a few minutes) and because the locations at which the phenomenon was observed gave signal subtenses smaller than the minimum 6-minute angle of our photometer. However, we made measurements of other representative incandescent and LED signals in the field at 100-m distance and as aligned with signal orientation as possible. Luminances were of an order similar to those of the respective laboratory signals, and chromaticity coordinates were within 0.02 of the respective laboratory signals.

Results

Experiment 1

Figure 3 shows the group mean data for the percentage of presentations in which the red signals were miscalled as orange/yellow in the high-illumination condition. Under high-illumination conditions (auxiliary projector on) and particularly at the longer testing distance of 10 m, a large percentage of the red signals were miscalled as orange/yellow with a defocus of +0.50 to +1.00 D. When the projector was turned off, the percentage of red signals reported to be orange/yellow tended to be zero at both testing distances.

All observers were able to appreciate that the red signal viewed through the top of the progressive lens corridor appeared orange/yellow. The mean power in the progressive corridor at which the participants reported the color change from red to orange/yellow was +0.84 ± 0.25 D, with a range from +0.62 to +1.25 D.

All observers appreciated the dynamic change in signal color perception from red to yellow when viewing through the manipulation of the Alvarez lens, to change power from zero through to positive defocus. Half the observers reported that the red signal appeared to change to orange then yellow, whereas the other half reported a change to yellow without an intermediate orange. The group mean power at which observers perceived the color change was +0.63 ± 0.11 D (range, +0.42 to +0.75 D).

The characteristics of the signal surround also had an important influence on the misperception of the red signal as orange/yellow, as shown in Table 1. As the black background increased in diameter from 22 to 50 mm, the percentage of times that the red signal was miscalled as orange/yellow decreased. The effect of increasing the size of the black annular surround had the effect of reducing the mean percentage of red signals miscalled as yellow from 59% to 22%. The addition of a large gray background only became effective in reducing the number of miscalled red signals as yellow when the background was dark grey, in response to which the misperceptions were reduced from 59% to 9% (a factor of six).

For the observer whose accommodation had been paralyzed and for the oldest observer (49 years) who had little accommodation, there was no change in signal color perception when the power of the Alvarez lens was changed in the negative direction.

The three observers who viewed the red target produced by the interference filter (dominant wavelength, 654 nm), which eliminated shorter wavelength light (e.g., orange and yellow), were unable to determine the color of the signal at 10 m, but all reported that it appeared to change to yellow at 5 m in the presence of positive defocus.

Experiment 2

Table 2 gives the time of day of the observations; the positions of the sun, in direction and altitude; and the distance ranges over which the color misperception was viewed by each of the observers at the three sites. The data show that the distance ranges over which train signal colors were misperceived were similar in both observers. The mean defocus necessary to produce the color misperception across all sites was +0.76 ± 0.12 D (range, +0.30 to +1.07 D; site 1: mean, +0.70 D; site

Table 1. Group Mean (SE) Percentage of Times that the Observers Miscalled a Red Signal as Orange/Yellow as a Function of the Extent and Relative Reflectance of the Background Surround (Auxiliary Projector On and +0.75 D Defocus)

	Backgrounds						
	6 mm*	12 mm*	18 mm*	22 mm*	50 mm*	Light Grey (54%)	Dark Grey (20%)
% Red signals called yellow	59.8 (9.8)	72.9 (9.8)	60.0 (11.9)	59.4 (10.9)	21.9 (12.7)	41.7 (14.5)	9.4 (4.3)

* Diameters.

Table 2. Observation Times, Sites, Position of the Sun and the Distance Ranges Over Which the Color Misperception Was Seen

		Sun Observations		Distance Ranges (m)	
Site	**Time of Day**	**Direction Relative to True North**	**Altitude of Sun**	**JW**	**DA**
Site 1: LED	8.25–9.05 AM	53°52′–46°48′	23°44′–30°46′	490–780	460–850
	11.25–11.45 AM	9°03′–2°13′	46°18′–46°45′	700–750	700
	2.40–2.57 PM	312°50′–309°42′	30°23′–27°28′	450–500	500–550
Site 2: incandescent	9.45–10.05 AM	38°31′–33°35′	36°50′–40°32′	510–610	530–610
	12.15–12.35 PM	352°19′–345°38′	46°30′–45°38′	500–700	500–750
	3.40–3.55 PM	302°58′–300°51′	19°48′–16°53′	450–650	500–700
Site 3: incandescent	10.05–10.25 AM	33°34′–28°10′	39°32′–41°52′	650–900	650–900
	12.35–12.55 PM	345°37′–339°15′	45°36′–44°13′	450–700	500–700
	4.00–4.12 PM	300°10′–298°37′	15°53′–13°30′	340–500	340–500

2: mean, +0.80 D; site 3: mean, +0.77 D; no significant differences between sites).

The defocus data of the two observers were combined to form mean values as a function of distance and time of day at each of the three viewing sites, to determine whether there were any systematic differences. These data are presented in Figure 4 for the signal at site 3.

The time of day when the signals were observed appears to have had the greatest effect on the range of distances over which the color misperception was viewed at each site. Each site was considered separately.

Site 1: LED Signal. When the signals were viewed from 8:25 to 9:05 AM, when the sun was almost directly behind them, the color misperception occurred over a range of almost 400 m (460–850 m). However, when the sun was higher, at approximately 90° to the signals at 11:25 to 11:45 AM, the color misperception was viewed over only a 50-m range (700–750 m). When the sun was shining more directly on the signals in the afternoon, the color of the signals could not be distinguished until the viewer was 550 m from them, and the color was misperceived over a 100-m range.

Site 2: Incandescent Signal. The signal was relatively dim and the color difficult to distinguish under certain viewing conditions because one of the filaments was not working at the time of the observations. In the morning when the sun was shining on the signal at approximately 90°, the color of the signal could not be judged until viewed at 610 m, and the color misperception was apparent until 510 m. At the other two observation times, when the sun was either at 50° to the signal or directly behind it, the color of the signals was apparent at longer distances, and the color misperception was viewed between 750 and 450 m.

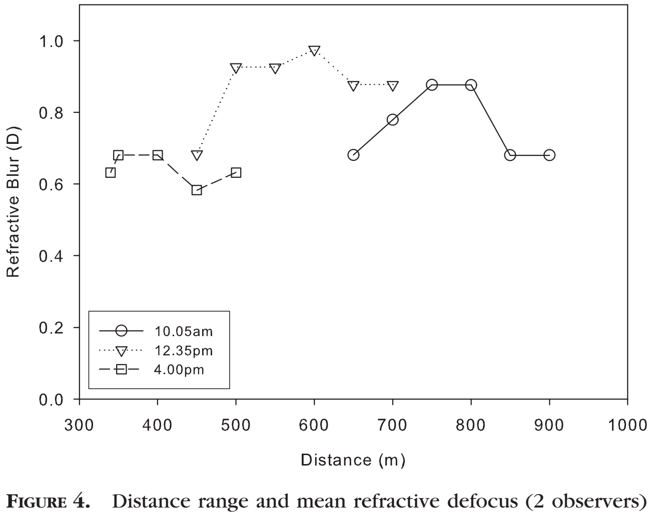

Figure 4. Distance range and mean refractive defocus (2 observers) necessary to produce the color misperception effect in experiment 2 while viewing train signals at site 3 between 10:05 and 10:25 AM, 12:35 and 12:55 PM, and 4:00 to 4:12 PM.

Site 3: Incandescent Signal. Time of day had more influence on the distance at which the color misperception could be viewed at this site relative to the other sites. In the morning, when the sun was at 90° to the signal, the color misperception was observed at 900 to 650 m; in the middle of the day, when the sun was shining at an angle of 140°, the signal color was misperceived from 700 to 450 m; and in the afternoon, when the sun was shining directly on the signal, the color misperception was viewed from 500 to 340 m.

The color misperception was not apparent at any distance, regardless of the amount of defocus, for either the LED or incandescent train signals under night viewing conditions.

Discussion

The initial observation of the train driver that red signal lights sometimes appear yellow was thus supported, both in a laboratory experimental simulation and in a quantitative field trial. The color misperception was not restricted to the wearing of progressive-addition lenses, but occurred in the presence of small amounts of positive defocus (typically +0.75 D) when signals subtended small angles (<1 min arc) under bright-illumination conditions.

The field trials demonstrated that there were no systematic trends in the amount of defocus needed to produce the color misperception for any of the three sites. However, in general, regardless of whether the signals were LED or incandescent, the amount of defocus necessary to produce the color misperception was of a relatively low order, which is in agreement with the laboratory-based studies and is typical of that encountered when signals were viewed through the top of a progressive lens corridor.

In terms of the distances at which the color misperception was observed, it was apparent that at longer distances (>900 m) no signal color could be judged; there was then a range of distances (which varied as a function of site and time of day) at which the color of the signal could be misperceived when it was viewed through small amounts of defocus; and, at closer distances, the color of the signal was correctly perceived regardless of the level of defocus. The time of day, which determined the position of the sun relative to the signals as well as its altitude, had a considerable effect on these distances. When the sun was shining directly on a signal, the color of the signal could not be judged until the observer was at relatively close distances; and, when the sun was directly behind the signal, the distances at which the color of the signal could be perceived were longer.

How can the color misperception be explained? The chromatic system mediating color vision is relatively insensitive to stimuli of small visual angles.[3,4] Defocusing the signal reduces its peak retinal illuminance, which results in a reduction in contrast relative to the surround, thus potentially making the test signal subthreshold for the chromatic system, although it may be visible via the luminance system. Chromatic thresholds rise more quickly than luminance thresholds for stimuli subtending less than 10 minutes. Extrapolating from published data, we found that the chromatic thresholds are estimated to be a factor of two times higher than the luminance threshold for the smallest stimuli used in these experiments (the extrapolation is based on expressing the thresholds for luminance and chromatic systems in similar units of cone contrast).[4] This is consistent with observers' reports that the red signals, although no longer appearing red, still appeared quite bright.

The color misperception may also be related to Abney's effect, in which high-intensity monochromatic light mixed with white light appears to change color, so that the perceived color of red light changes toward yellow.[5,6] In the laboratory, defocusing the signal caused the light from the signal to be mixed with that of the white background on the retina; and when black (>22 mm wide), rather than white, surrounds were used, the color misperception was reduced from 60% to 22%.

The color misperception is not influenced by chromatic aberrations[7] because the color shifts for the red signals are in the wrong direction (positive defocus should improve the focus of red relative to that of yellow) and the red interference filter used to produce the red signals effectively eliminates shorter wavelength light (~580–595 nm) that might appear yellow. Similarly, it cannot be explained by the Bezold-Brücke effect, which describes the change in subjective hue that occurs when the intensity of monochromatic lights varies,[8] as this effect requires an increase in the intensity of a red light rather than a decrease, for it to appear yellow. If the intensities of red signals decrease as they do in the field when the lamp housing becomes dirty and the light sources age, they would be expected to appear more rather than less reddish.

Previous research has considered how the appearances of surface colors can be affected by target size, with targets of a size similar to those in our study (1–2 minutes) resulting in apparent tritanopia.[9] However, the color appearance of red was reported to be unaltered. The phenomenon we observed was unlikely to have resulted from atmospheric conditions, as the appearance of red signals has been shown to be robust to variations in atmospheric haze.[10]

It has also been reported that participants' refractive error types can influence the red-green ratio for larger targets (1.6° diameter) in a color-matching task with yellow. Wienke[11] observed that the more myopic the participant, the higher the green-red ratio, and the more hyperopic the participant, the lower the green-red ratio. Although interesting, this phenomenon is unrelated to the phenomenon reported in the current study, because of the different nature of the tasks and because the participants in the earlier study had fully corrected visual acuity, rather than being exposed to small defocus levels, as in our study.

The color misperception is not limited to train signals, as two of the authors have noted it when viewing traffic signals at long distances. The train driver is likely to have noted it originally because the distance portion of his progressive-addition lenses was slightly too strong (small amount of positive defocus), and it could have been exacerbated by slight tilts of the head upward to look through the top of the intermediate corridor of the lenses. It is imperative that people in the transport industries who rely on signal colors to make critical decisions have regular vision examinations and wear up-to-date spectacle prescriptions. There is no reason to bar the wearing of progressive-addition lenses for such tasks, but it is important that considerable care be given to their fitting so that people are not looking through the intermediate corridor during distance tasks and thus experiencing unwanted positive defocus.

This phenomenon may not have been previously recognized in color vision experiments, as they typically employ large stimuli (>1° diameter) to stimulate the chromatic system preferentially in observers whose acuity is optimally corrected.[3] These conditions are clearly not the case in many real-world situations in which color misperceptions have serious implications for safety.

Acknowledgments

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References

1. Alvarez LW. Development of variable-focus lenses and a new refractor. *J Am Optom Assoc*. 1978;49:24–29.
2. Humphrey WE. A remote subjective refractor employing continuously variable sphere-cylinder corrections. *Opt Eng*. 1976;15:286–291.
3. King-Smith PE, Carden D. Luminance and opponent-color contributions to visual detection and adaptation and to temporal and spatial integration. *J Opt Soc Am*. 1976;66:709–717.
4. Chaparro A, Stromeyer CF, Kronauer RE, Eskew RT. Separable red-green and luminance detectors for small flashes. *Vision Res*. 1994;34:751–762.
5. Kurtenbach W, Sternheim CE, Spillmann L. Change in hue of spectral colors by dilution with white light (Abney effect). *J Opt Soc Am A*. 1984;1:365–372.
6. Kaiser PK, Boynton RM. *Human Color Vision.* 2nd ed. Washington DC: Optical Society of America; 1996.
7. Atchison DA, Smith G. *Optics of the Human Eye.* Oxford, UK: Butterworth-Heinemann; 2000:180–193.
8. Vimal RLP, Pokorny, J, Smith, VC. Appearance of steadily viewed lights. *Vision Res*. 1987;27:1309–1318.
9. Middleton WEK, Holmes MC. The apparent colors of surfaces of small subtense: a preliminary report. *J Opt Soc Am*. 1949;39:582–592.
10. Middleton WEK. *Vision through the Atmosphere.* Toronto, Ontario, Canada: University of Toronto Press; 1958:154–174.
11. Wienke RE. Refractive error and the green/red ratio. *J Opt Soc Am*. 1950;40:589–595.