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ORIGINAL ARTICLE

Low levels of refractive blur increase the risk of colour misperception of red train signals

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Abstract

Purpose: Red signals signify danger in a range of situations, including train operations. Importantly, misperception of a red signal as yellow can have serious safety implications. This study investigated the effects of lens blur on incorrect colour perception of red signals, which has been implicated in previous train crashes.

Methods: Participants included 15 young (26.6 ± 4.6 years) and 15 older (55.8 ± 3.1 years) visually normal adults. Red and yellow wayside train signals were simulated for two brightness levels (dim, bright) using a custom-built projection system. The effect of blur (best-corrected refraction [No Blur], +0.25 DS, +0.50 DS, +0.75 DS, +1.00 DS, +1.25 DS) on the number of incorrect colour perception responses of the signals was recorded. The order of conditions was randomised between participants.

Results: For incorrect responses to the red signal, there were significant main effects of blur ($p < 0.001$) and signal brightness ($p < 0.001$) and a significant interaction between blur and brightness ($p < 0.001$). The effects of blur were greater for the dim compared to the bright signals, with significantly higher colour misperceptions for the dim signal for +0.50 DS blur and higher, compared with No Blur. Colour misperceptions of the yellow signals were low compared with that of the red signals, with only +1.25 DS blur resulting in a significantly higher number of incorrect responses than No Blur ($p < 0.001$). There were no effects of age for the red or yellow colour misperceptions ($p > 0.19$).

Conclusions: Low levels of blur (+0.50 DS to +1.25 DS) resulted in a significant misperception of the red signals as orange-yellow, particularly for dim signals. The findings have implications for vision testing and refractive correction of train drivers to minimise the possibility of colour misperception of red train signals.

KEYWORDS
ageing, colour perception, refractive blur, train signals

INTRODUCTION

Red signals are a warning of danger in a range of situations in the transport industry, including driving trains on rail networks. Red train signals must be correctly differentiated from yellow, given that they indicate both the need to stop and a different braking response to other signal aspects. Despite the tests for colour vision that train drivers have to pass, in some instances drivers fail to detect and recognise signals.[1] This can result in a Signal Passed At Danger (SPAD) and the train proceeding through unsafe points ('rail intersections'). Such events are considered important precursors to collisions and derailments;[1] both can be associated with fatalities and injuries. Despite modern safety practices, SPADs remain an identifiable event in safety statistics. Since 2000, in the UK there have been approximately 300 SPADs per year, and this rate has remained stable, except during the COVID-19 pandemic when train traffic was reduced.[2] In 2020–2021, five of these SPADs resulted in the conflict point being passed, with potential for passenger train collisions.[2] In Australia, there were 260 SPADs reported in 2019–2020,[3] with stable numbers reported over the past 5 years, except for some increased numbers for light rail.[3]

Previous research described a situation where a train driver reported that red train signals appeared yellow when viewed at long distances through his progressive-addition lenses. Wood et al.[4] explored these effects in a field and laboratory-based study and confirmed the effect observed by the train driver. Small amounts of optical defocus, such as those experienced when looking through the intermediate corridor of progressive-addition lenses or with sub-optimal refractive correction with a single vision distance lens, were shown to cause misperception of the red colour of train signals at long distances, typically between 600 and 900 metres, where the signal light is small (~1 min of arc). Underlying reasons for this phenomena were suggested to include Abney's effect, where high-intensity light mixed with white light appears to change colour, such that red moves towards yellow.[4] In a separate laboratory-based study, Gupta et al.[5] also explored the factors affecting the colour appearance of small targets and found that the characteristics of the target surround were important, with colour changes not occurring when the surround was a uniform white.[5] This study also reported that correcting higher-order monochromatic aberrations had no effect, but that longitudinal chromatic aberrations (LCA) were linked with the phenomenon; when LCA was neutralised with an achromatizing lens the effect disappeared, when LCA was doubled it was more vivid for some subjects and when reversed in direction, some observers were able to see it but with negative instead of positive defocus. Gupta et al.[5] suggested that there are additional defocus dependent neural mechanisms contributing to the change in colour appearance.

The effects of optical blur on colour misperception of red signals is important given that uncorrected refractive error is a significant cause of reversible visual impairment,[6,7] which increases significantly with age.[8,9] While train drivers are required to undergo vision testing, the visual standards and the regularity of testing vary widely across different countries. Visual acuity with or without corrective lenses ranges from 6/6 (UK) to 6/12 (USA) in the better eye and 6/12 in the worse eye for most standards, except Australia (6/18 worse eye) and Canada (6/15 worse eye).[10–13] The frequency of testing ranges from every 5 years (Australia and UK) to every 3 years (US) after commencement of employment, with more frequent testing with increasing age (typically over 50 years).

There have been no studies exploring the potential effects of age on the misperception of train signal colours, with a younger age range of participants reported in a previous study (20–49 years).[4] The question of whether age affects the colour misperception of train signals is important to explore given the older age profile of the train driver workforce,[14,15] and those likely to be using progressive-addition lens spectacle designs, which may induce blur when viewing through the intermediate corridor.

This research sought to investigate further the effects of optical blur on the perception of signal colour, and included an older age group to explore whether age impacted the colour perception of train signal lights.

Key points

- Low levels of blur (+0.50 DS to +1.25 DS) can result in misperception of small red signals (simulating long-range train signals) as orange-yellow, particularly for dim signals.
- Colour misperception of small red signals as orange-yellow can result when observers are not wearing their optimal optical correction or when viewing through the intermediate portion of a progressive-addition lens.
- Findings of colour misperception of small red signals as orange-yellow have implications for rail safety, visual standards and testing frequency of train drivers to ensure safe operation of trains.

METHODS

Participants

Participants included 30 adults with normal vision (15 young: aged 20–35 years; 15 older: aged 50–65 years; 15 male, 15 female) who were recruited from the staff and students of Queensland University of Technology and their associates; none of the participants were train drivers. All participants had best-corrected distance visual acuity of

0.10 logMAR (Snellen 6/7.5) or better in each eye and passed the Ishihara pseudoisochromatic plate test (24-Plate edition), where the fail criteria was three or more errors on the first 17 plates.[11] The Ishihara plates were illuminated with LED office lighting providing 670 lux at the plates. Participants were excluded if they had any known ocular disease. The study adhered to the tenets of the Declaration of Helsinki and was approved by the Queensland University of Technology Human Research Ethics Committee. All participants were provided with an explanation of the nature of the study and procedures, and written informed consent was obtained.

All participants underwent an eye examination conducted by an experienced optometrist, which included ophthalmoscopy, slit-lamp biomicroscopy and fundus photography to confirm that they were free of ocular disease and thus eligible for study inclusion. Best-corrected distance visual acuity was determined by subjective refraction using maximum plus for best visual acuity for each eye separately as well as binocularly, using an Early Treatment Diabetic Retinopathy Study (ETDRS) chart at 5 m and luminance of 130 cd/m^2, scored on a letter-by-letter basis (−0.02 log units correct). Binocular letter contrast sensitivity was measured with the best-corrected distance correction using the Pelli-Robson letter chart at 1 m, with a +0.75 DS working distance correction in place, and scored on a letter-by-letter basis (0.05 log units correct).

Experimental setup

Light signals were constructed using a custom-built light box consisting of a single light source (7 W 5000 K LED globe) with appropriate chromatic (Wratten filters #22 and #92) and ND filters to provide similar intensities and spectral distribution chromaticities to that of four different train signal lights. Luminance and chromaticity measurements of the targets and other components of the experimental set-up were made with a calibrated LMK 5 colour video photometer (TechnoTeam Bildverarbeitung, technoteam.de) and Topcon BM-7A (Topcon, Topcon.com). The chromaticity co-ordinates satisfy the requirements of the Australian Rail Track Corporation (ARTC) Engineering standards which provide guidance for colour light signals in New South Wales, Australia.[16] The luminance levels of the signals were also based on these ARTC standards, where the luminous intensity for long range signals should exceed 200 cd (6,500 cd/m^2) but there is no colour distinction, and also on the variations for different colours used in the Traffic Signal Standards[17] (minimum luminous intensities of 520 cd (16,550 cd/m^2) for yellow and 250 cd (7,960 cd/m^2) for red at 200 mm diameters). The luminance values of the signals are given in Figure 1. It should, however, be noted that the ARTC standard also states that the maximum luminous intensity of the signals should not exceed 750 cd (24,000 cd/m^2), which the bright yellow signal exceeded by a factor of 1.5.[16]

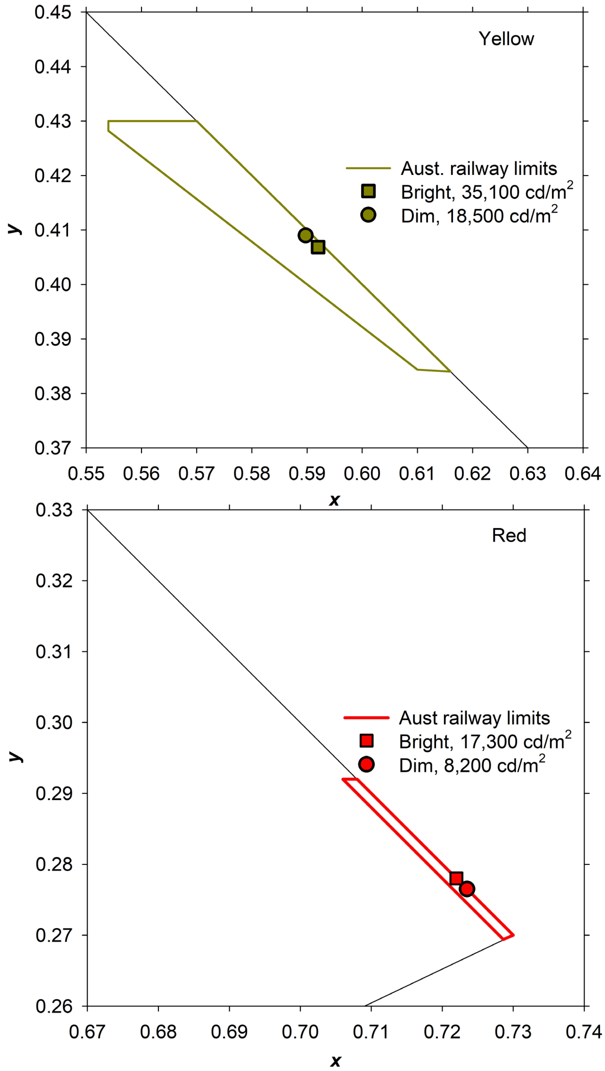

FIGURE 1 Chromaticity coordinates of the red and yellow signals and the Australian wayside railway signal limits. Luminance values for the signals are specified

The experimental setup is shown in Figure 2. A 6 mm black circular disc with a 2 mm aperture was mounted immediately in front of the light box, to produce a signal that subtended 0.7 min of arc at the testing distance and was presented for 3 s. The dimensions of the light and annulus were in the same proportion as signal lights in Australia. A brightly illuminated surround field of 1,810 cd/m^2 (CIE co-ordinates of the background surround: $x = 0.318$; $y = 0.378$) was produced by an auxiliary projector (Epson) to simulate the effects of viewing signals in bright photopic conditions (where the train signal colour misperceptions have been reported).[4,18] A custom-built software program controlled the rotational position of the filter wheel, number of trials per colour and the signal presentation time, which generated a randomised sequence for the order of presentations, based on the required number of trials and signal target colours for each of the vision conditions.

Participants wore a trial frame incorporating the following lenses fitted into a standard 35 mm trial lens holder, to

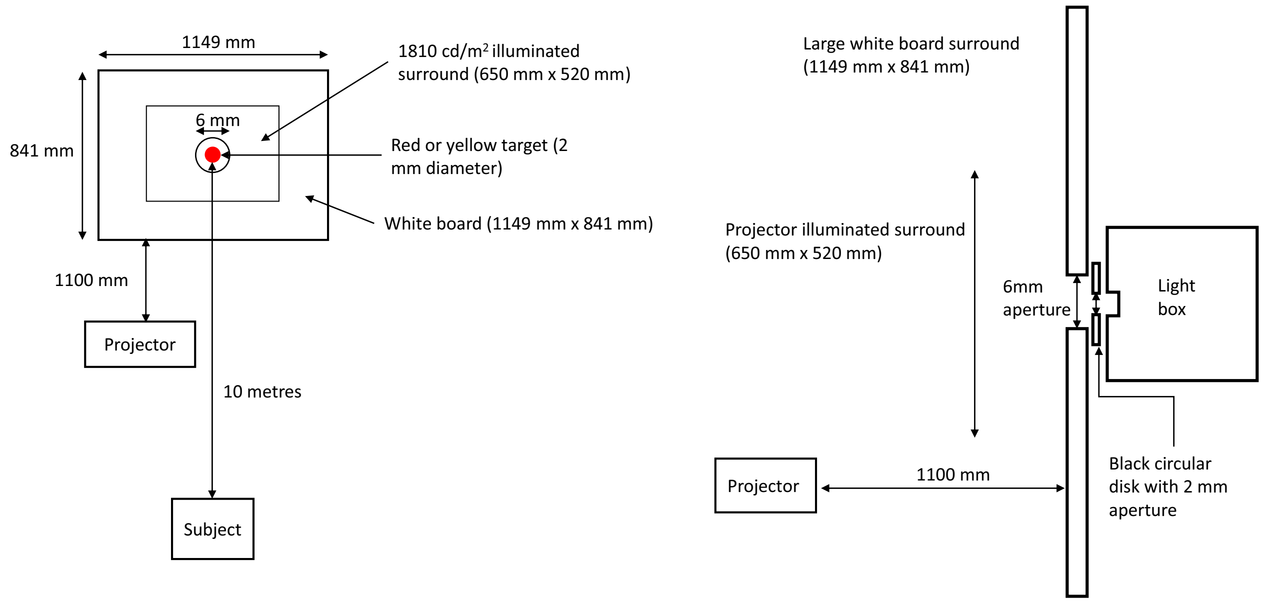

FIGURE 2 Schematic representations of the experimental setup showing the testing distances (left) and side-view (right). *Note:* Diagram not to scale

incorporate participants' best-corrected refractive correction in front of both eyes: No Blur, and 5 blur levels (+0.25 DS, +0.50 DS, +0.75 DS, +1.00 DS and +1.25 DS); these levels of blur were selected based on previous research.[4]

For each blur condition, there were six presentations for each of the four signals, with a total of 24 signal trials per vision condition. The sequence of the vision conditions was varied between participants, using a counter-balanced Latin square design, to minimise learning and order effects. The experiment took approximately 45 min (6 presentations × 4 train signals × 6 vision conditions). Participants were instructed that there would be a series of small, coloured lights under different viewing conditions, which would either be red or orange-yellow in colour. The term orange-yellow was used given our experience in a previous study[4] that participants described the perception of the yellow signal as being 'yellow', 'orange-yellow' or 'orange'. Thus, we asked participants to "call out what colour the light appears to you – whether you would call it red, or orange-yellow. If the colour appears in-between, call out what it appears closer to – more red or more orange-yellow." No feedback was provided to participants regarding whether their signal colour judgement was correct or incorrect.

Statistical analyses were performed using SPSS statistical software v25.0 (IBM, ibm.com) and the level of significance was set at $p < 0.05$. Participants' demographic and vision characteristics are presented using descriptive statistics (means, standard deviations and proportions). Group differences were examined using independent sample *t*-tests for continuous variables and chi-square tests for categorical variables. The outcome measure for the signal colour perception was the proportion of incorrect responses for each vision condition in response to the red and yellow signals separately. Repeated measures regression analysis using Linear Mixed Models (LMM) were performed to assess differences in colour misperception. All models included random intercepts for participants, to take into consideration the repeated measures design, and used maximum likelihood estimation. Any significant interactions were further tested using simple effects models to understand the nature and direction of these identified relationships. Pairwise comparisons were made using the Least Significant Difference (LSD) method.

TABLE 1 Demographic and vision characteristics of the study participants (means ± standard deviations)

	Young ($n = 15$)	Older ($n = 15$)
Age (years)	26.6 ± 4.6	55.8 ± 3.1
Gender		
Male, *n* (%)	7 (47)	8 (53)
Female, *n* (%)	8 (53)	7 (47)
Visual acuity (logMAR)	−0.13 ± 0.06	−0.13 ± 0.06
Contrast sensitivity (logCS)	1.93 ± 0.08	1.91 ± 0.07

RESULTS

Table 1 provides participant demographic and visual characteristics. The mean ages of the younger and older participants were 26.6 ± 4.6 years (range 20–35 years) and 55.8 ± 3.1 years (range 50–65 years), respectively, and there was no significant sex difference between groups ($\chi^2 = 0.13$, $p = 0.72$). Mean binocular visual acuity across all participants was −0.13 ± 0.06 logMAR (6/4.8^{+1}), with no significant difference in visual acuity between groups ($t_{28} = 0.00$, $p = 1.00$). Overall mean binocular log contrast sensitivity for all participants was 1.92 ± 0.08, with no significant difference between groups ($t_{28} = 0.70$, $p = 0.49$).

Figure 3 represents the colour misperceptions of the red and yellow signals as a function of optical blur and signal brightness. A LMM was performed to investigate the relationship between colour misperception of the red signal and blur, which included blur (6 levels), signal intensity (2 levels: dim vs. bright) and age group. There were significant effects of blur ($F_{5,330} = 16.27$, $p < 0.001$) and signal brightness ($F_{1,330} = 65.14$, $p < 0.001$), and a significant blur × signal brightness interaction ($F_{5,330} = 11.74$, $p < 0.001$). There was no significant effect of age ($F_{1,30} = 0.64$, $p = 0.43$). Colour misperception of red was higher for increasing levels of blur, and the significant interaction was evidenced by the greater effect of higher levels of blur for the dim red signals. Overall, colour misperception of the bright red signal was low, with +0.50 DS showing a small but significantly higher level of misperception than No Blur ($p = 0.01$), while the other blur conditions were not significantly higher than No Blur ($p > 0.09$). However, there was a pronounced increase in the colour misperception of the dim red signal, rising to 43.9 ± 34.3% for +1.25 DS. In pairwise comparisons, colour misperception of the dim red signal increased significantly when blur was +0.50 DS or higher ($p = 0.001$) than for No Blur.

Miscalling the yellow signal as red occurred relatively infrequently compared with miscalling the red signal as orange-yellow, with less than 1% of all trials where yellow was miscalled as red for the No Blur condition. An LMM investigated the relationship between colour misperception of the yellow signal and blur, which included blur (6 levels), signal intensity (2 levels: dim vs. bright) and age group. There was a significant effect of blur ($F_{5,330} = 8.71$, $p < 0.001$), but no effect of signal brightness ($F_{1,330} = 3.30$, $p = 0.07$), no significant blur × signal brightness interaction ($F_{5,330} = 0.97$, $p = 0.44$) and no effect of age ($F_{1,30} = 1.82$, $p = 0.19$). There were similar levels of colour misperception of the yellow signal for the lower levels of blur compared with the No Blur condition, with only the +1.25 DS significantly higher ($p < 0.001$) than No Blur. The frequency of colour misperception of the yellow signal was similar for both brightness levels (Figure 3).

DISCUSSION

In this laboratory-based study, the effect of low levels of blur on the colour misperception of red and yellow signals was explored to understand better whether these factors could contribute to train incidents due to misjudgement of the colour of red train signals. A key finding was that colour misperceptions of the dim red signal were significantly affected by blur, particularly at levels of blur of +0.50 DS or higher.

The findings regarding the effects of blur support those of Wood et al.,[4] who reported that a significantly higher proportion of red signals were miscalled as orange-yellow when viewing with blur levels between +0.50 to +1.00 DS. The proportion of colour misperception was similar for dim red signals in their study compared with the present investigation, but lower for the bright red signal, which is likely to be due to variations in the experimental setups, such as the luminance of the signal lights and the illumination and extent of the surround. The sample size in the current study was also larger and included a broader range of ages.

In the present study, the misperception of the colour of the red signal with increasing blur was influenced significantly by signal brightness, with stronger effects noted for increasing blur when viewing the dimmer red signals. These findings highlight the importance of ensuring adequate signal brightness is maintained, particularly if there are reductions in light output over their lifespan or transmittance changes in the signal covers (dirty or cloudy

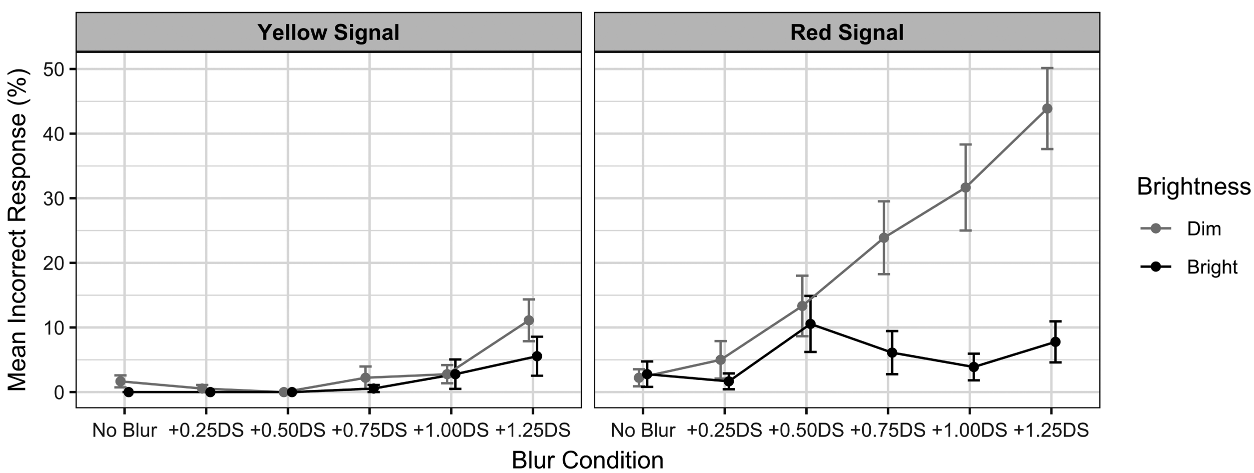

FIGURE 3 Group mean incorrect responses (%) for the yellow signal (left) and red signal (right) as a function of blur condition and signal brightness. Errors bars represent ±1 SEM (standard error of the mean)

covers), and reinforce the importance of regular maintenance of signals to ensure that the brightness levels comply with standards.

The findings for the yellow signal demonstrate a low frequency of colour misperception, which were not significant except for the +1.25 DS blur condition relative to No Blur, and much lower than those for the colour misperception of the red signal. While there are low levels of misperception of yellow signals as red, even for the higher levels of blur and dimmer signal brightness levels explored in this study, these have limited safety implications as these signals are not used to signify danger.

This study also explored the effects of age on colour misperception by including observers similar in age to those of train drivers who reported the signal colour misperceptions.[4,18] Age group did not affect the magnitude of colour misperceptions resulting from lens blur. This is likely to be because age-related changes in ocular media tend to reduce transmittance of shorter wavelengths (blue light), while mid to longer wavelength transmittance is relatively unaffected.[19,20]

The findings of this laboratory-based study provide the basis for making recommendations regarding visual testing and refractive correction of train drivers to minimise the possibility of colour misperception. It is important to note that the potential for colour misperception occurred when the distance portion of the correction was too strong (positive blur of +0.50 DS and above). Thus, wearers of progressive-addition lenses may report this effect if viewing the signal through the portion of the lens intended for intermediate vision, or the effect may also occur with single vision distance spectacles if the correction is under or over-corrected. Thus, train drivers should have their eyes examined on a regular basis to ensure that they have the optimum spectacle/contact lens correction for distance vision when they drive trains. This is important, given that most of the standards for railway employees who need to perceive the colour of wayside train signals correctly in order to complete their job requirements safely, require a range of visual acuity levels (6/9 to 6/15), but do not require 6/6 except for the UK standard that stipulates 6/6 in the better eye.[10–13] This is relevant to the current study as small amounts of defocus, that are unlikely to reduce visual acuity below these standards, can cause colour misperception of red signals. These levels of defocus could result when looking through the intermediate corridor of progressive-addition lenses, or with sub-optimal refractive correction for either hyperopic or myopic individuals. Optometrists undertaking vision testing and dispensing optical corrections for train drivers should be informed of the potential colour perception problem and take the necessary steps to avoid it. In particular, progressive-addition lenses should be fitted appropriately to ensure that train drivers are not viewing distance targets, such as train signals and signs, through the intermediate vision corridor.

It is important to acknowledge that these findings are based on a controlled experimental laboratory study, where train signals were simulated using combinations of a range of filters and light sources, and may not be directly generalisable to all environmental conditions and signal lights. It should also be noted that the brightness of the bright yellow target was greater than that specified in Australian Train Signal Standards, but given that target brightness had no effect on the results for the yellow target this is unlikely to have had any impact on the findings. Importantly, the results were shown to be consistent with the field observations reported previously.[4,18] It should also be noted that a potential limitation of this study was that participants were given the option to describe the signals as either red or orange-yellow, rather than red or yellow, given that in our previous study,[4] participants described the perception of the yellow signal as being 'yellow', 'orange-yellow' or 'orange'. Future work could explore the effects of low levels of blur on colour naming, where participants are shown examples of red signals and instructed to respond "stop", and a yellow signal and instructed to respond "caution" which would relate more specifically to the incidence of SPADs.

In summary, the findings support previous research,[4] showing that misperception of red signals can result when observers are not wearing their optimal optical correction (i.e., their spectacle or contact lens prescription could be over or under corrected) or when viewing through the intermediate portion of a progressive-addition lens.[4] These findings should inform recommendations regarding visual standards and frequency of testing of train drivers to ensure the safe operation of trains.

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CONFLICT OF INTEREST

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

AUTHOR CONTRIBUTIONS

Joanne M Wood: Conceptualization (lead); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); supervision (equal); writing – original draft (lead). **Alex A Black:** Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); supervision (equal); writing – review and editing (equal). **David A Atchison:** Conceptualization (equal); data curation (supporting); formal analysis (supporting); funding acquisition (equal); investigation (equal); methodology (equal); writing – review and editing (equal). **Gregoire S Larue:** Conceptualization (equal); data curation (supporting); funding acquisition (equal); methodology (equal); project administration (equal); writing – review and editing (equal).

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