Progressive Myopia or Hyperopia Can Be Induced in Chicks and Reversed by Manipulation of the Chromaticity of Ambient Light

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Purpose. To determine whether progressive ametropia can be induced in chicks and reversed by manipulation of the chromaticity of ambient light.

Methods. One-day-old chicks were raised in red light (90% red, 10% yellow–green) or in blue light (85% blue, 15% green) with a 12 hour on/off cycle for 14 to 42 days. Refraction was determined by streak retinoscopy, and by automated infrared photoretinoscopy and ocular biometry by A-scan ultrasonography.

Results. Red light induced progressive myopia (mean refraction ± SD at 28 days, −2.83 ± 0.25 diopters [D]). Progressive hyperopia was induced by blue light (mean refraction at 28 days, +4.55 ± 0.21 D). The difference in refraction between the groups was highly significant at $P < 0.001$. Induced myopia or hyperopia was axial as confirmed by ultrasound biometry. Myopia induced by 21 days of red light (−2.21 ± 0.21 D) was reversed to hyperopia (+2.50 ± 0.29 D) by subsequent 21 days of blue light. Hyperopia induced by 21 days of blue light (+4.21 ± 0.19 D) was reversed to myopia (−1.23 ± 0.12 D) by 21 days of red light.

Conclusions. Rearing chicks in red light caused progressive myopia, while rearing in blue light caused progressive hyperopia. Light-induced myopia or hyperopia in chicks can be reversed to hyperopia or myopia, respectively, by an alteration in the chromaticity of ambient light. Manipulation of chromaticity may be applicable to the management of human childhood myopia.

Keywords: myopia, animal model, refractive error

Interest in factors influencing ocular growth and refractive development has been stimulated by the increasing prevalence of childhood myopia in many parts of the world, especially East Asia, with the highest recorded prevalence in Singapore,[1] and also by experimental work that has shown that myopia can be induced in the young of many species by manipulation of the visual input in early life.[2–7] In its higher degrees myopia carries a risk of sight-threatening complications, such as myopic choroidoretinal atrophy, submacular neovascularization, or retinal detachment, and from associated conditions that include glaucoma and cataract.

In relation to lens-induced experimental ametropia, it has been suggested that the retina is sensitive to the vergence of light traversing it,[8] and is able to distinguish between convergent and divergent light, and to modify ocular growth in response to this. It has also been suggested that the retina may use cues from longitudinal chromatic aberration to modify ocular growth of the young eye.[9,10]

It is well established that accommodation responds to chromaticity,[11,12] accommodation being increased red light and decreased blue light as would be expected from the fact that longer wavelengths of red light are focused more posteriorly in the retina than shorter wavelengths of blue light. The refractive difference between red and blue light is estimated at approximately 2 diopters (D).[13]

In relation to the possible effects of chromaticity on ocular growth and refractive development, Seidemann and Schaeffel[11] showed that accommodation in humans and chicks was responsive to chromaticity, being less in blue (440 nm) light than in red (>600 nm) light. In chicks following 2 days of rearing in monochromatic red or blue light, there was a small but significant alteration in refractive status when chicks were refracted in the dark. The refractive change persisted following cycloplegia, making it unlikely that the effect was due to accommodation. Kroger and Binder[14] suggested that the reduced accommodative tonus accompanying a reduction of long wavelengths of light while viewing print on green paper might also reduce the risk of developing myopia, although this was not investigated further.

In monochromatic light when visual information is restricted to one focal plane, it has been stated that the incident vergence of light determines emmetropization,[8] and that compensation to lens-induced defocus in chicks requires intact accommodation and fails to occur following ciliary nerve

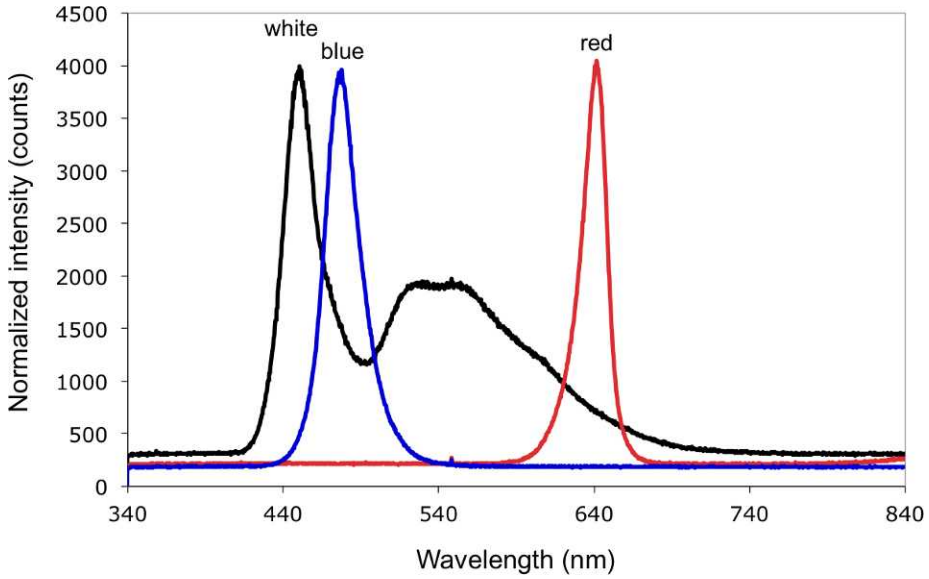

FIGURE 1. Spectral emission curves for the three types of LEDs used for chick rearing. White-emitting LEDs had a broad emission spectrum (410–790 nm) with a high peak at 440 nm and a lesser broad peak at 536 nm. The emission of blue-emitting LEDs ran from 395 to 550 nm with a sharp peak at 477 nm. The emission of red-emitting LEDs ran from 550 to 680 nm with a major peak at 641 nm. Light from red and blue LED emission contained a proportion of green wavelengths, but no blue in the case of red-emitting LEDs and no red in the case of blue-emitting LEDs.

section, indicating that accommodation plays a role in emmetropization.[8] In an earlier study, Rohrer and associates[15] showed that the refractive status of chicks was not altered and that emmetropization occurred normally when chicks were reared in monochromatic red or blue light. Negative lens-induced myopia could still occur, however, in conditions of monochromatic light.

In relation to the possible effects of chromaticity on ocular growth and refractive development, it has been shown that time spent outdoors, irrespective of the nature of the activity involved, is protective against the development of myopia.[16] The chromaticity of light outdoors in relation to refractive development is an aspect that has not so far been investigated, although this has been suggested as a factor of relevance.[17] The chromaticity of light outdoors is characterized by an excess of blue and green wavelengths and a deficit of red wavelengths,[18] other than at sunrise and sunset when red wavelengths predominate. Additionally, in daylight, outdoor lighting is many times brighter than indoor lighting. Light of an intensity comparable with light outdoors has been shown to slow the development of form deprivation myopia in chicks.[19]

It has also been shown that fluorescent lighting is associated with an increased prevalence of hyperopia[20] and astigmatism[21] as compared with tungsten lighting. These results suggested that the chromaticity of indoor lighting produced by tungsten or fluorescent lighting might influence refractive development in children.

We have previously hypothesized that an imbalance of excitation between the tips and bases of the photoreceptor outer segments (OS) might alter the pattern of growth of the young eye,[22] excess excitation of the OS tips compared with their bases stimulating ocular elongation and myopia, and an excess excitation in the OS bases as compared with their tips inducing hyperopia. We have reported preliminary data from a small sample of chicks that showed that those reared in mainly red light developed a low degree of myopia over a short period of time (14 days), while blue light rearing induced a low degree of hyperopia over a similar time period.[22]

The purpose of the present study was to determine whether chromatic manipulation over a longer period of time would result in a progressive increase in the induced ametropia in chicks and additionally, to determine whether myopia induced by red light rearing or hyperopia induced by blue light rearing could be reversed by subsequent rearing in blue or red light, respectively.

METHODS

All experiments were performed in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research, and were approved by the Institutional Animal Care and Use Committee (IACUC) of the Singapore Experimental Medicine Centre (SEMC) located in the Singhealth General Hospital (SGH). The SEMC has accreditation by the Association for Assessment and Accreditation of Laboratory Animal Care International (AAALAC).

One-day-old chicks in batches of four to six were raised in a custom-built, rectangular enclosure that measured 70 cm in length, 35 cm in width, and 25 cm in height. The enclosure was light tight and lined internally with vertical black and white stripes as accommodative cues. The spatial frequency of the stripes was between 4 and 8 cycles/deg for chicks near the center of the enclosure. Four banks of light emitting diodes (LEDs) with 30 LEDs in each bank were distributed around the inner side of the lid of the enclosure to ensure a uniform distribution of light within the enclosure.

To achieve a disparity in the excitation of the OS tips and bases we decided to make use of longitudinal chromatic aberration. This concept was not new and had been unsuccessfully attempted previously, using monochromatic light as already indicated.[15] To obtain an imbalanced distribution of excitation along the OS, it appeared to us that lighting with a sufficient content of midwavelength green, to which the chick eye[9,15] and human eye[23] are most sensitive, would be necessary to maintain accommodation so that the focal plane for green wavelengths would lie in the OS midpoints. With green as a reference, and an excess of red wavelengths, excitation in the OS tips would be greater than in their bases, while with some green and an excess of blue wavelengths, excitation in the OS bases would be greater than in their tips.

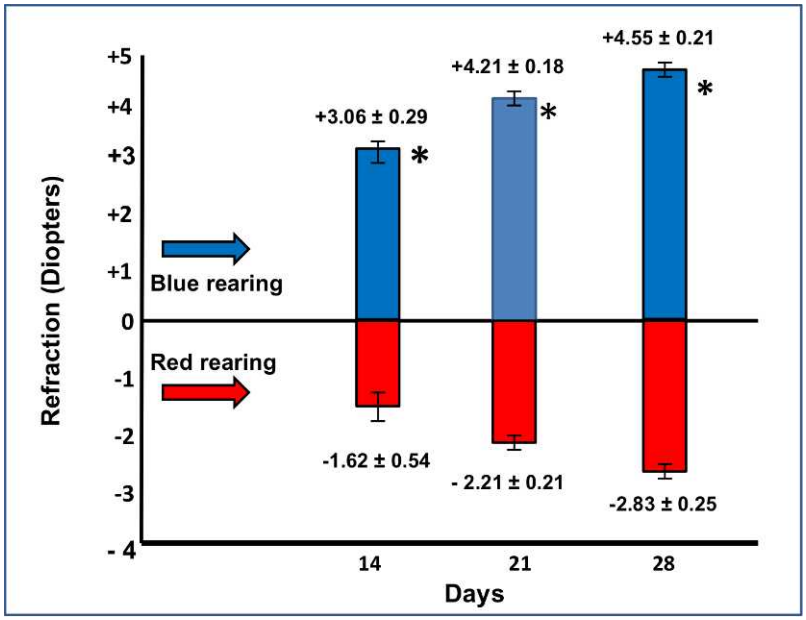

FIGURE 2. One-day-old chicks ($n = 16$) raised in red light became myopic at 14 days, more myopic at 21 days ($n = 6$), and still more myopic at 28 days ($n = 6$), while those ($n = 19$) raised in blue light became hyperopic at 14 days, more hyperopic at 21 days ($n = 6$), and still more hyperopic at 28 days ($n = 6$). The differences in mean (±SD) myopic and hyperopic refractive errors were significant at each time interval (*$P \leq 0.001$). At 14 days induced myopia or induced hyperopia were each significantly different from emmetropia (zero refractive error) ($P < 0.001$). *Error bars*: 1 SD.

Experiments were carried out with red-, blue-, and white-emitting LEDs with a 12 hour on/off periodicity (6 AM–6 PM). The emission characteristics of the LEDs used were determined with a high-resolution spectrometer (HR 2000; Ocean Optics, Dunedin, FL) (Fig. 1). The white-emitting LEDs had a broad-emission spectrum extending from 420 to 790 nm with a sharp peak in the blue at 440 nm, a broader low-amplitude crest in the green centered at 536 nm, and a long low-amplitude tail into the far red. The light emitted from blue-emitting LEDs (also referred to as blue light in this paper to avoid repetition) had an emission spectrum in the blue running from 440 to 495 nm with a sharp peak at 477 nm, a significant content of green wavelengths (approximately 15%) running from 495 to 550 nm but no red. The light emitted from red-emitting LEDs (also referred to as red light) had an emission spectrum in the red running from 600 to 680 nm with a sharp peak at 641 nm and a proportion of green–yellow wavelengths (approximately 10%) between 550 and 600 nm but no blue. Luminance at various points within the enclosure was measured with a photometer with a chromatic detector (LX107; Digital Instruments LT Lutron, Taipei, Taiwan). A series of readings at the center of the enclosure at the level on which the chicks were raised was carried out for each type of LED to allow the relative luminance for each of the LED types to be compared. The luminance at the center of the enclosure was 33.37 cd/m^2 for red-emitting LEDs, 34.44 cd/m^2 for blue-emitting LEDs, and 117.32 cd/m^2 for white-emitting LEDs.

The enclosure was supplied with a constant temperature-controlled air supply between 28°C and 32°C. There was remote provision of food and water (ad libitum) and remote enclosure cleaning. Chicks were raised in the enclosure in selected lighting conditions for periods of 14 to 42 days. During this period, chick behavior and health were monitored by closed-circuit television (CCTV).

At the end of each period of rearing in specific lighting conditions, chicks were removed from the enclosure and sedated with an intramuscular injection of ketamine 30 mg/kg and xylazine 3 mg/kg that also caused pupillary dilatation and cycloplegia as confirmed by automated infrared photoretinoscopy[24] that records both accommodated and nonaccommodated refraction. Refraction of each eye was determined by streak retinoscopy in earlier experiments, and additionally by automated infrared photoretinoscopy in later experiments. Only the streak retinoscopy results are reported here. In a parallel experiment, there was an excellent correlation between streak retinoscopy and automated photoretinoscopy ($r = 0.994$, $n = 58$ eyes, $P < 0.001$), validating the more subjective results of streak retinoscopy. The mean of six measurements of spherical refraction in the horizontal axis as measured by streak retinoscopy was taken as a measure of refraction. Ocular axial lengths and vitreous chamber lengths were determined by A-scan ultrasonography at a frequency of 20 MHz (Sonomed Ultrasound A-1500; Sonomed, Inc., Lake Success, NY) with each determination being the average of six separate measurements.

In further experiments, newborn chicks raised in light from red-emitting LEDs underwent refraction and biometry at 14 and 21 days, and were then exposed to light from blue-emitting LEDs for a further 21 days with refraction and biometry repeated at 14 and 21 days of blue light rearing. Additionally, newborn chicks were reared in light from blue-emitting LEDs for 21 days, followed by rearing in light from red-emitting LEDs for a further 21 days, and again with refraction and biometry at 14 and 21 days of blue light rearing and at 14 and 21 days of subsequent red light rearing. At the conclusion of each experiment, euthanasia in the sedated animal was by an overdose of pentobarbitone administered intramuscularly.

Data from one eye chosen at random from each chick in each experimental condition were used for subsequent analyses. Comparisons between mean refractions and mean vitreous and ocular axial lengths in chicks raised in differing chromatic conditions were made by two-tailed Student's *t*-tests for sample sizes of n greater than or equal to 10 or by Mann-Whitney U test for sample sizes n less than 10. The normal distribution of these measured parameters was confirmed by frequency histograms.

To establish differences in the chromaticity of outdoor daylight and indoor artificial light, we determined the spectral

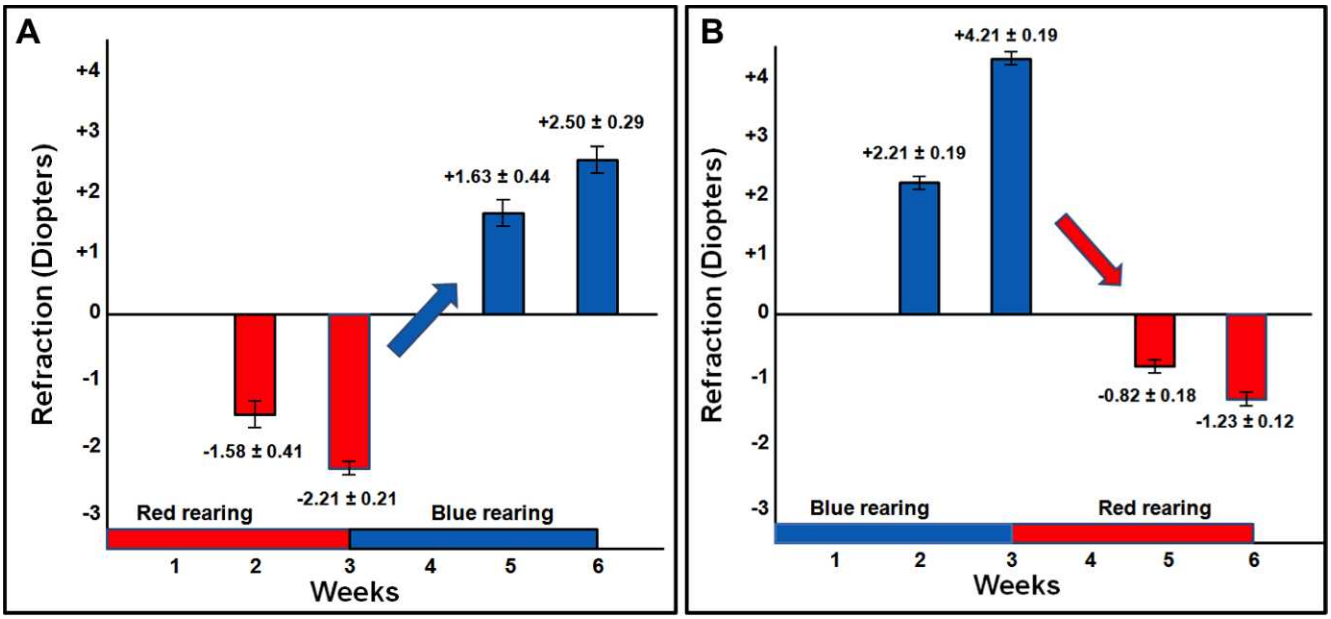

FIGURE 3. (**A**) One-day-old chicks ($n = 6$) raised in red light became myopic at 14 days and more myopic at 21 days, but this was reversed to hyperopia after 14 days of rearing in blue light with a further increase in hyperopia after 21 days of blue light rearing. (**B**) One-day-old chicks ($n = 6$) raised in blue light became hyperopic at 14 days and more hyperopic at 21 days, but this was reversed to myopia after 14 days of rearing in red light with a further increase in myopia after 21 days of red light rearing. *Error bars*: 1 SD.

composition of a variety of outdoor and indoor scenes using the line profile analysis procedure available from Igor software (WaveMetrics, Portland, OR). To minimize the effects of automatic white balance in digital cameras, both outdoor and indoor scene photographs were taken with identical camera settings and, purposefully, without any attempt to simulate color constancy by manual adjustment of white balance. The method of analysis used provided relative differences in chromaticity rather than absolute values. The spectral composition of tungsten light and of long-lasting fluorescent lamps was also determined using the same computer program and, subsequently, by spectroscopy (Ocean Optics USB2000-VIS-NIR; Ocean Optics) of a white sheet of paper illuminated by a 60-W tungsten lamp or by a long-lasting fluorescent lamp (compact fluorescent lamp, CFL) of equivalent wattage.

RESULTS

Newborn chicks raised in red light ($n = 16$) became progressively myopic with a mean ± SD refractive error at 14 days of −1.62 ± 0.54 D that increased at 28 days ($n = 6$) to a mean myopia of −2.83 ± 0.25 D (range, −2.50 to −3.25 D). Chicks raised in blue light ($n = 19$) became progressively hyperopic with a mean refractive error at 14 days of +3.06 ± 0.29 D that increased to a mean hyperopia of +4.55 ± 0.21 D at 28 days ($n = 6$; range, +4.00 to +4.75 D) (Fig. 2). Even by 14 days the difference in the mean refraction of chicks raised in either red or blue light was highly significant ($P < 0.001$). The red light–induced myopia and the blue light–induced hyperopia at 14 days were each significantly different to emmetropia (zero refractive error) ($P < 0.001$). A small number of chicks ($n = 5$) that were raised in white light (that had a slight excess of blue wavelengths), became mildly hyperopic at 14 days (mean +1.60 ± 0.25 D) (range, +1.25 to +2.00 D). On average, the vitreous chamber length of myopic chicks raised in red light for 14 days (5.55 ± 0.11 mm) was significantly longer than in hyperopic chicks raised in blue light for 14 days (4.73 ± 0.72 mm, $P < 0.001$).

Chicks ($n = 6$) made myopic by rearing in red light for 21 days (mean −2.21 ± 0.21 D; range, −2.00 to −2.50 D) rapidly became hyperopic (mean +2.50 ± 0.29 D; range, +2.00 to −3.50 D) when the lighting was changed to blue light for a further 21 days (Fig. 3A), while chicks ($n = 6$) made hyperopic by rearing in blue light for 21 days (mean +4.21 ± 0.19 D; range, +4.00 to +4.75 D) became myopic (mean −1.23 ± 0.12 D; range, −1.00 to −1.25 D) when lighting was changed to red light for a further 21 days (Fig. 3B). The refractive error of chicks following blue light rearing for 21 days was significantly different to that following subsequent 21 days of red light rearing ($P < 0.001$) as was the difference in refraction following 21 days of red light rearing compared with that following subsequent blue light rearing for 21 days ($P < 0.001$).

During red light rearing followed by blue light rearing (Fig. 4A) and blue light rearing followed by red light rearing (Fig. 4B), body weight showed a linear increase with no change in the rate of growth when the chromaticity of rearing light was changed, and with a similar mean weight (and size) of chicks at the end of each period of rearing.

There was a gradual increase in mean ocular axial length during red light rearing, and this increase continued for the first 14 days of blue light rearing but ceased during the third week. The most notable finding was that the mean vitreous chamber length increased at a faster rate than mean ocular axial length during red light rearing, but decreased markedly and rapidly during subsequent blue light rearing (Fig. 4A).

In blue light rearing followed by red light rearing (Fig. 4B) a linear increase in mean body weight was not affected by either blue or subsequent red light rearing. The mean vitreous chamber length decreased between days 14 and 21 of blue light rearing as did the mean axial length, although to a lesser degree than the vitreous chamber length. During subsequent red light rearing, both the mean axial length and mean vitreous chamber length increased, the vitreous chamber length increasing at a faster rate than axial length during the first 2 weeks of red light rearing, but at approximately the same rate during the third week of red light rearing (Fig. 4B).

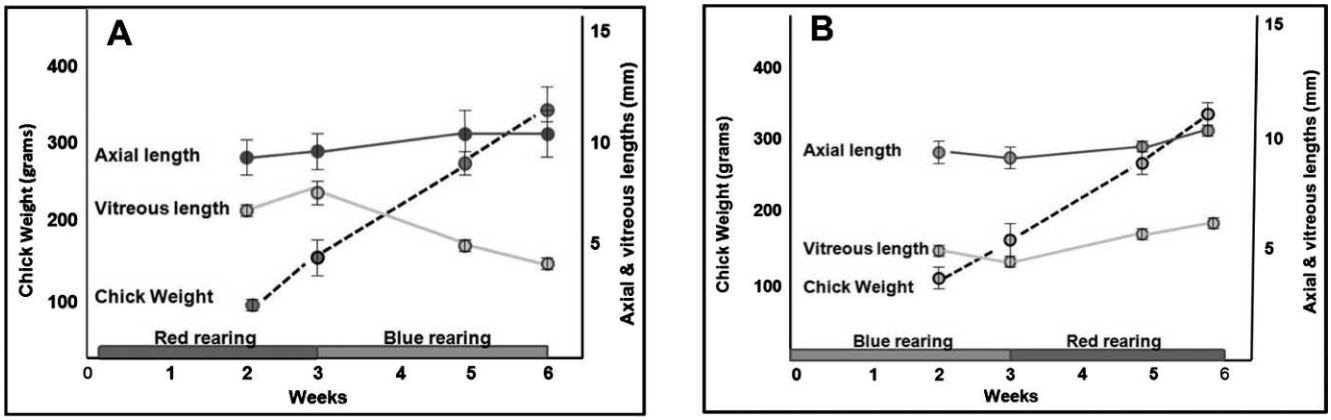

FIGURE 4. (**A**) Graphs of mean body weight (g), mean ocular axial length (mm), and mean vitreous chamber lengths (mm) at various time intervals of the chicks in Figure 3 that were initially raised in red light for 21 days and subsequently in blue light for 21 days. Body weight increased linearly during red and blue light rearing. Axial lengths increased slowly during red light rearing and during the first 14 days of blue light rearing, but the increase ceased during the third week of blue light rearing. Vitreous chamber lengths increased more rapidly than axial lengths during red light rearing, but decreased rapidly and markedly during blue light rearing. (**B**) Similar parameters for chicks raised initially in blue light for 21 days followed by red light for 21 days. Body weight increased linearly during blue or red light rearing. Axial lengths decreased during blue light rearing and vitreous chamber lengths decreased at a faster rate. In subsequent red light rearing, vitreous chamber lengths increased at a slightly faster rate than axial lengths. Differences in vitreous chamber and axial lengths were probably due to changes in choroidal thickness (see text). *Error bars*: 1 SD.

Analysis of photographs of outdoor scenes in bright daylight conditions showed a preponderance of blue and green wavelengths and a deficit of longer red wavelengths (Fig. 5). In contrast, tungsten light had a continuous emission spectrum that contained a preponderance of longer red wavelengths, a proportion of green wavelengths, but much less blue (Fig. 6A). The spectral emission of a CFL, of a type that is replacing tungsten lamps for domestic use, revealed a discontinuous emission spectrum with a major peak in the red at 600 nm, a lesser peak in the green at 550 nm, a very much smaller peak in the blue at 430 nm, and virtually no UV emission (Fig. 6B). In spite of the differences in spectral continuity, the emission spectrum of the tungsten lamp resembled that of the CFL both having a preponderance of red emission, a significant amount of green and a reduced amount of blue emission.

DISCUSSION

We have demonstrated, for the first time, that significant progressive axial myopia can be induced in chicks by rearing in light emitted by red-emitting LEDs, and that progressive hyperopia can be induced by rearing chicks in light emitted by blue-emitting LEDs, a greater than 7 D difference in refraction being demonstrated by 28 days between chicks reared in red light as compared with blue light. Additionally in chicks, we have shown that myopia induced by red light rearing can rapidly be reversed to hyperopia by subsequent blue light rearing, and conversely that hyperopia induced by blue light rearing can be reversed to myopia by subsequent red light rearing.

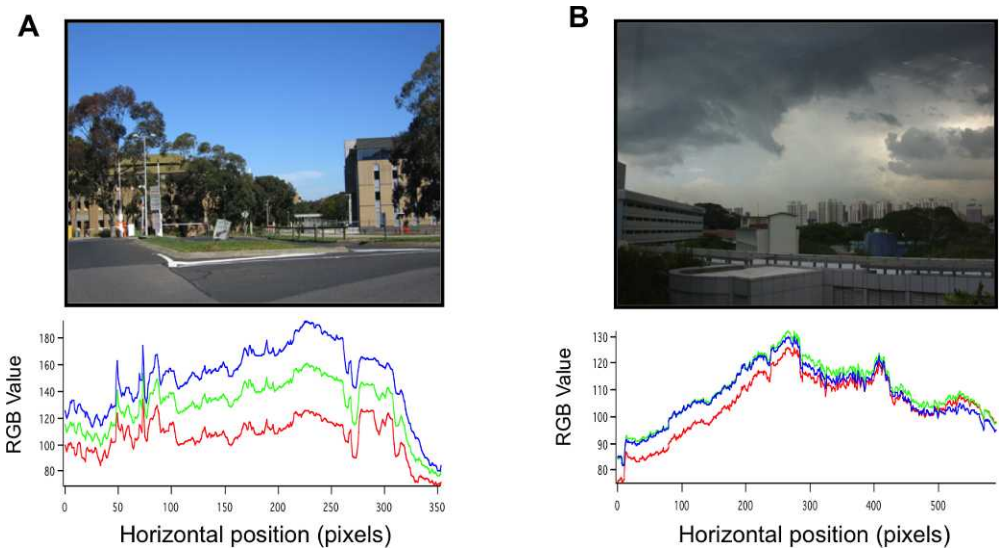

FIGURE 5. Two outdoor scenes photographed without adjustment of white balance. *Below* each photograph is a computer analysis of the red, green, and blue content of the photographed scenes. (**A**) In sunny conditions there is a preponderance of blue and green wavelengths and a reduced amount of red. (**B**) In cloudy conditions the contributions of red, green, and blue wavelengths are equal.

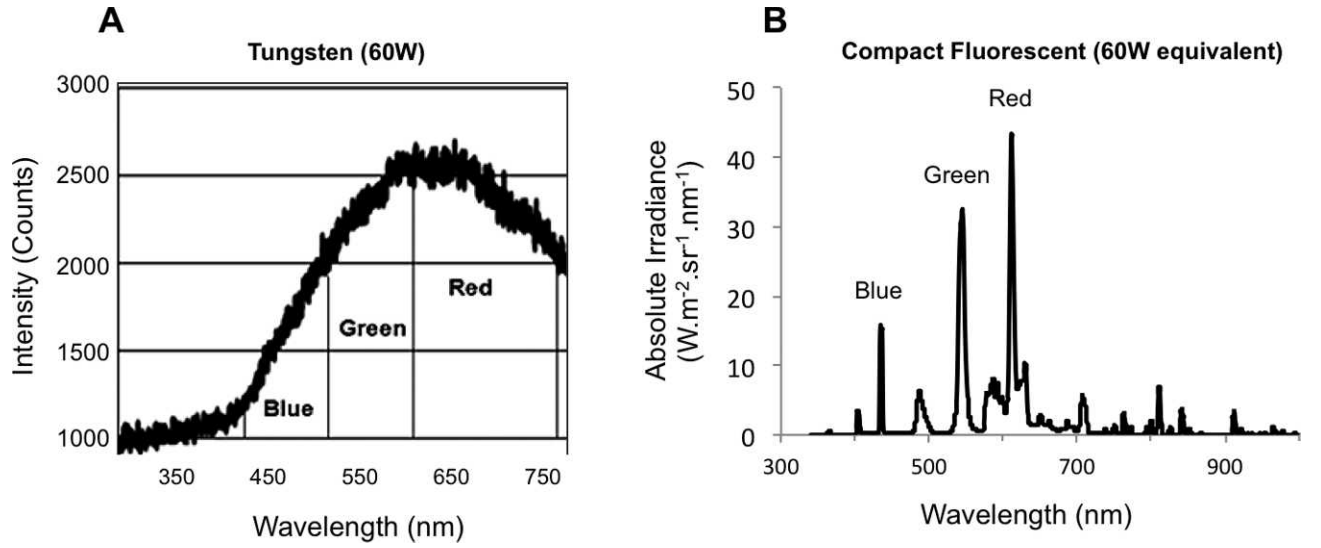

FIGURE 6. (**A**) Visible spectral emission of tungsten lighting. (**B**) Visible spectral emission of a CFL. The spectral emission of tungsten light is continuous, whereas that of CFL is discontinuous. In each case, however, longer red wavelengths are predominate. Both spectra contain a significant content of green and a reduced content of blue.

Unlike earlier studies[15] that showed no differences in refractive status between chicks raised in red or near-UV blue monochromatic light and that chicks could emmetropize normally in either chromatic condition, the progressive myopia or hyperopia we have induced in chicks by manipulation of the chromaticity of light required a broad range of wavelengths from red to green to induce myopia, and from blue to green to induce hyperopia. In our experiments, chicks were exposed to strong accommodative cues in addition to differing chromaticities. An absence of accommodative cues in some earlier experiments[15] may have contributed to the failure to demonstrate any effect on refractive development in chicks exposed to red or blue monochromatic light. Our hypothesis requires accommodation to be effective, and as already indicated, there is evidence that intact accommodation is a requirement for compensation to lens-induced ametropia.[8]

In our experiments, although the luminance of red- and blue-emitting LEDs was approximately equal, the emission from white-emitting LEDs was more than three times brighter. It has been shown that the intensity of light in which chicks are raised can affect refractive development, low intensities inducing myopia, and high intensities, hyperopia.[25] Light of high intensity also slows the development of form-deprivation myopia.[19] The degree of hyperopia induced by blue light rearing observed in our experiments was much greater than that induced by white light, although the opposite would have been expected if the effect had been due to the intensity of light, for the intensity of blue light was less than one-third of white light. The altered growth and refraction were thus likely to have been associated with chromaticity and not light intensity.

Although the waveguide properties of the receptor OS[26] might be thought not to support our hypothesis, internal reflection along the OS is likely to maintain the convergence of red wavelengths and the divergence of blue wavelengths with an increasing excitation along the OS, in the case of the former and a decreasing excitation in the case of the latter. Additionally, it has been shown[27] that excitation of the OS, following absorption of a photon, is restricted to a narrow band of the excited OS with no proximal or distal spread of excitation, a situation that would be necessary to achieve a differential distribution of excitation between tips and bases of the OS.

It is accepted that our suggested hypothesis remains highly speculative unless it can be supported by the demonstration of a skewed distribution of excitation along the length of the OS following rearing in either red or blue light. At present, the mechanisms underlying the demonstrated effects of chromaticity on ocular and refractive development remain conjectural.

Rucker and Wallman[10] have suggested that the response of the eye to chromatic aberration may be determined by a relative defocus of red wavelengths focused behind the L-cones when blue wavelengths are focused within the S-cones, and a relative defocus of blue wavelengths (focused proximal to the S-cone bases) when red wavelengths are focused within the L-cones; therefore resulting in a reduced contrast of the image in the L-cones in the former situation and a reduced contrast of the image in the S-cones in the latter situation, with an imbalance of contrast between stimulated L- and M-cones as compared with S-cones.

In our experiments, red light contained no blue wavelengths and blue light contained no red. Nevertheless as red light that induced myopia contained a proportion of green wavelengths, an in-focus green image in the M-cones might have had a higher contrast compared with a blurred defocused red image behind the tips of the L-cone OS. The image with a lower contrast would have a lower photon catch than the in-focus higher contrast image, and the consequent effects on ocular growth and refractive development in this situation might have been be due to a disparate excitation of L- and M-cones. A similar increased contrast in M-cones compared with S-cones in blue light might be the stimulus to the development of hyperopia.

Although elucidation of the mechanisms involved was not part of our project, the chick model of induced ametropia that we have developed and its reversibility will provide a useful test bed for the investigation of the factors underlying the effects of chromaticity on refractive development.

The changes induced in refraction by manipulation of the chromaticity of light in which chicks were raised were axial in nature, induced myopia being associated with longer vitreous chamber lengths than in chicks with induced hyperopia. In the former situation, the posterior segment of the eye elongates

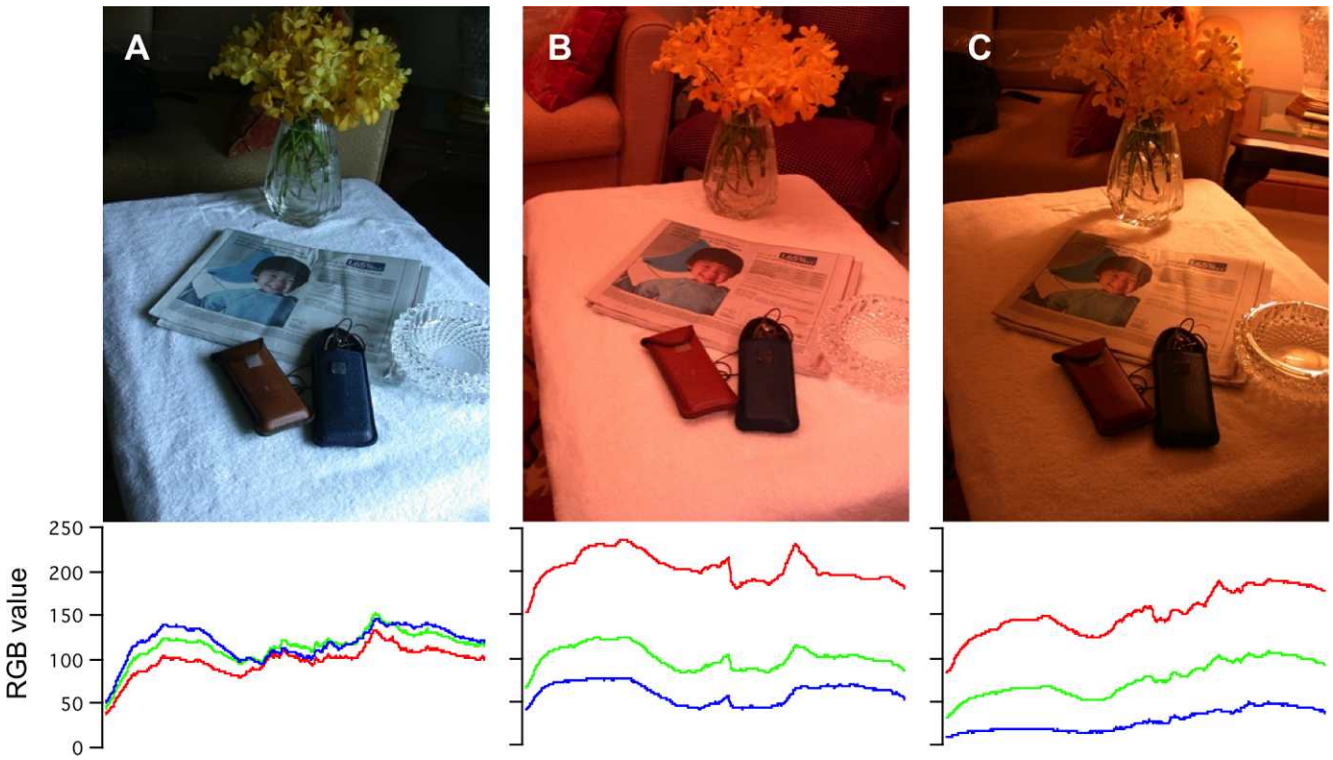

FIGURE 7. The same indoor scene photographed with identical camera settings and no attempt to simulate color constancy in (**A**) daylight, (**B**) tungsten light, and (**C**) CFL. *Below* each photograph is a computer analysis of the red, green, and blue content of the photographed scenes. The differences in chromaticity are relative and obvious. The average contributions of red, green, and blue across the horizontal plane are shown quantitatively, by computer analysis, for each type of lighting.

away from the direction of incident light, while in the latter the opposite occurs. While an increase in vitreous chamber lengths in line with increasing myopia is easy to accept, the rapid reduction in measured vitreous chamber lengths that occurred on changing previously red to blue lighting is less so, but likely to have been due to an increase in the thickness of the vascular choroid, for in experimental lens-induced ametropia in chicks, changes in vitreous chamber length can be rapid and have been associated with changes in choroidal thickness.[28] Differing effects on axial length and choroidal thickness have been demonstrated in experiments on compensation to plus or minus lens wear in chicks, when tested in red or blue light,[29] or to grid patterns simulating a chromatic shift in the position of the focal plane in the retina.[10] Similarly, the differences in the rate of change between axial lengths and vitreous chamber lengths at various times during either red or blue light rearing in our experiments are likely to have been due to alterations in the thickness of the choroid.

The magnitude of the induced refractive errors was less than might have been expected from the differences in vitreous chamber lengths alone. In our experiments, at 21 days the mean vitreous chamber length of eyes of chicks raised in red light (6.11 ± 0.06 mm) was greater than in those raised in blue light (4.35 ± 0.08 mm), a difference of 1.76 mm. The measured difference in refraction of 6.42 D is much less than would be expected on the basis of vitreous chamber lengths alone. The changes in corneal curvature and other related anterior segment changes that occur during emmetropization may have proceeded unaffected by the chromaticity of rearing light, an aspect that requires further investigation. If so, the greater flattening of the cornea in larger myopic eyes would act to reduce the myopia that would be expected from the increase in vitreous chamber length, and conversely the steeper corneal curvature in smaller hyperopic eyes would act to reduce the hyperopia associated with a reduced vitreous chamber length. It has to be accepted, however, that the disparities between the chromaticity induced changes in refraction and the corresponding alterations in ocular biometry remain unexplained.

Unlike refractive errors induced experimentally by plus or minus lens wear in early life that cease to develop further when the induced refractive error matches the strength of the lens inducing the error,[6] excess red or blue light will continue to be a stimulus to altered ocular growth for as long as the young eye is capable of responding to the chromaticity of incident light. In the chick, the progressive myopia induced by red light rearing measured 0.75 D per week, while rearing in blue light induced a hyperopia of just over 1 D per week. Currently, it is not known for how long the chick eye is capable of responding to the chromaticity of light in which chicks are reared.

Although outdoor activity has been shown to be protective against the development of myopia,[30,31] there is a considerable disparity in the reported associations between such factors as near-work and indoor activity as risk factors for childhood myopia. It has been shown, however, that sports activity outdoors is protective against myopia while similar activity indoors is not.[32,33] The increasing prevalence of myopia has been associated with increasing urbanization.[34] Urbanization involves a change from a largely outdoor rural lifestyle to an indoor lifestyle with an increased exposure to artificial light. As already indicated tungsten light commonly used indoors has an emission spectrum resembling that which induces myopia in chicks (Fig. 6A). Tungsten lamps, however, are rapidly being replaced by fluorescent CFLs.

Fluorescent lamps in general have a discontinuous emission spectrum with a variable content of shorter and longer

wavelengths depending on the phosphor used. The emission spectrum of fluorescent lights can have a color temperature similar to that of tungsten incandescent lamps at 2700 K to as high as 4000 to 6500 K in cool-white or daylight fluorescent lights. The former lights with a lower color temperature have a significant content of longer wavelength red emission giving a warm tungsten-like illumination, while the latter with high color temperatures produce a blue-white light.[35] In the study by Czepita and others[20] of children whose homes were lit by either tungsten or fluorescent lighting, it was found that there was a higher prevalence of hyperopia among those exposed to fluorescent lighting than among those whose homes were lit by tungsten lamps, but the emission characteristics of the fluorescent lamps is not known. If these were earlier versions with a significant content of short wavelengths in their emission spectrum[35] the results of their study would support the hypothesis that increased exposure to artificial light may be a factor in the increasing prevalence of childhood myopia.

Our analysis of the spectral emission of a compact fluorescent lamp of a type that is replacing tungsten lamps for domestic use (Fig. 6B) showed a very discontinuous spectrum with a preponderance of longer red wavelengths, some green, but a reduced content of blue wavelengths and might therefore pose as great a risk of inducing myopia, as in children using tungsten lighting if the results we have shown in chicks can be extrapolated to children.

The very large differences in the color of objects lit by artificial light or by daylight is not usually apparent to the observer as a result of color constancy, but is easily observed in photographs such as those illustrated in Figure 7 provided the image is only a small section of what the eye with a full visual field can see. Automatic white balance in digital cameras and color constancy each depend, in their own way, on an analysis of the luminosity of objects of differing color over a wide area. White balance in digital cameras (and color constancy in humans) fails when only a restricted area is photographed (or viewed) as in the photographs in Figure 7 taken with identical camera settings in manual mode and, purposefully, without any attempt to simulate color constancy by manual adjustment of white balance. Although not absolute in terms of color content, the photographs readily demonstrate the relative differences in chromaticity resulting from differing light sources. The relative differences in chromaticity of different light sources obtained from the photographs were similar to those obtained by spectroscopy.

In conclusion, we have demonstrated that significant and progressive axial myopia can be induced in chicks by rearing in red light (with 10% of green/yellow light), and that hyperopia can be induced by rearing chicks in blue light (with 15% of green light). Additionally, we have shown that in chicks, myopia induced by red light rearing can rapidly be reversed to hyperopia by subsequent blue light rearing, and conversely that hyperopia induced by blue light rearing can be reversed to myopia by subsequent red light rearing. These novel findings highlight the effects that the chromaticity of ambient light can have on ocular and refractive development, and may help to explain the protective effect against myopia of outdoor activity and the possible implication of artificial light in the increasing prevalence of childhood myopia. As a corollary, manipulation of the chromaticity of light to which the eyes are exposed may be of value in the management of childhood myopia or its prevention.

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