

LED lighting undermines visual performance

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Article

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Abstract

Life evolved under broad spectrum sunlight, from ultraviolet to infrared (300-2500nm). This spectrally balanced light sculpted life's physiology and metabolism. But modern lighting has recently become dominated by restricted spectrum light emitting diodes (350-650nm LEDs). Absence of longer wavelengths in LEDs and their short wavelength dominance impacts physiologically, undermining normal mitochondrial respiration that regulates metabolism, disease and ageing. Mitochondria are light sensitive. The 420-450nm dominant in LEDs suppresses respiration while deep red/infrared (670-900nm) increase respiration in aging and some diseases including in blood sugar regulation.

The retina is mitochondrial rich with high metabolic demand and rapid aging. When those working exclusively under blue dominant LEDs are supplemented with a sunlight spectrum for 2 weeks, their colour perception improves significantly across the blue-yellow and red visual axes. Hence, LEDs suppress normal colour vision.

Importantly, mitochondria communicate across the body with systemic impacts following regional light exposure. This likely involves shifting patterns of serum cytokine expression, raising the possibility of wider negative impacts of LEDs on human health particularly, in the elderly or in the clinical environment where individuals are debilitated. Changing the lighting in these environments could be a highly economic route to improved public health.

Introduction

Ambient light impacts on human health. Sunlight under which life evolved extends over approximately 300-2500nm. Older incandescent lighting common until recently has a similar spectral range. But because our visual sensitivity is limited to 400-700nm we are unaware of infrared light (approximately 700nm-2500nm). However, light in the built environment is now driven by light emitting diodes (LEDs), whose restricted spectrum (approximately 390-700nm) is designed around our visual sensitivity and consequently is economic [1]. Typical LED lighting produces strong elements in the shorter blue wavelengths (420-450nm) with a second yellow peak which drops swiftly above 650nm, with little light above 750nm [1]. Short wavelength exposure in animals in the range of 420-450nm reduces mitochondrial function, which provides the energy for cellular physiological performance in the form of adenosine triphosphate (ATP). 420-450nm reduces mitochondrial complex activity and ATP production, in a highly conserved manner [2,3]. This is associated with increased body weight [4] and reduced lifespan [5]. This negative influence is likely due to mitochondrial absorption by porphyrin that may increase proinflammatory oxygen singlet production reducing mitochondrial demand for glucose [3]. Deeply penetrating longer wavelengths (approximately 700nm plus) that are largely absent from LEDs but present in sunlight, incandescent lighting and fire light increase mitochondrial performance and ATP production particularly when challenged by age or disease [6,7]. This increased performance is associated with increased lifespan and mobility in animals [8,9] and improved visual performance and enhanced blood glucose regulation in humans [10, 11]. Hence, exposure to different ends of the

spectrum impacting on mitochondria can translate into changes in key physiological metrics. Similar changes are found at the population level. Those spending more time in sunlight generally have improved health including cardiovascular disease and the incidence of cancer. They also have lower rates of type 2 diabetes [12,13]. In this study we confront the impact of LED lighting on human visual performance by measuring colour contrast detection in an LED illuminated working environment that is then supplemented with incandescent lighting. The hypothesis is that LED lighting suppresses mitochondrial function in the retina and that this can be corrected by introduction of wide spectrum incandescent lights. The results highlight the potential damaging influence of LED lighting on human performance.

Results

Light assessment in the experimental environment. Figure 1 shows the front exterior of the Here East building using infrared imaging at ground level where experiments were undertaken. The windows are completely infrared reflective due to their blocking film and hence mirror like. Figure 2 is an infrared image from inside the building looking out through the open doorway. Only infrared light coming through the open door and its reflectance can be seen, not light coming through adjacent windows. Hence, the building is relatively impervious to infrared light.

The internal lighting at Here East was provided by an array of ceiling mounted standard LED units. Spectral analysis of the lighting within the building is shown in Fig. 3 and was provided by an array of ceiling mounted standard LED units. The blue curve is the LED lighting in the building compared against incandescent lighting in black and red. Hence, the work environment which was deep in the building received no daylight and was devoid of any infrared illumination. The lighting:

Light assessment was also undertaken at bench level where individual subjects worked. This is shown in Fig. 4. This confirmed the ascent of any part of the infrared spectrum in the work environment.

Visual responses to shifts in spectral lighting. Exposure to 60W incandescent luminaires, which have a wider spectrum than LEDs extending into the infra-red [1], resulted in significant improvements in visual performance in all experimental subjects across both the protan and tritan visual ranges. Improvements in both tritan and protan were of the order of 25%. Hence, significant improvements were uniform across visual ranges (Fig. 5). This is unlike experiments where specific red/infrared ranges have been used in LED devices, for example via 670nm, where visual improvements have been biased towards tritan function [10].

Figure 5 shows the results of both individual subjects on the left and also changes in the groups on the right. In spite of the universal improvement in visual function, in both tritan and protan range there was considerable variability between subjects. This variability validates the inclusion of a repeated measures design and the use of a sign test in the analysis. In all cases protan thresholds were lower than tritan consistent with previous studies [10].

At the end of the 2 week period the incandescent luminaries were removed and the subjects returned to an exclusively LED dominated light working environment. They were then retested at 4 and 6 weeks. In experiments where 670nm alone has been used, rather than the wide spectrum infrared produced by incandescent lighting, visual improvements decline in approximately a week [10]. However, following incandescent light exposure improvements remain unchanged across both visual domains at both 4 and 6 weeks. Hence, the impact of broad-spectrum incandescent light not only resulted in balanced improvements in colour contrast but also these improvements lasted much longer than previous interventions with restricted red/infrared ranges [10].

An independent control group was used in addition to a before and after experimental design. Again, data between individuals was varied on both visual metrics. However, over a 2 week period there were no significant changes in proton or tritan visual thresholds (Fig. 6).

Discussion

We demonstrate that the visual performance of those working under standard LED is significantly improved by exposure to incandescent lighting that has a spectrum similar to daylight with an extensive infrared component. These data are consistent with the hypothesis that LED lighting undermines human visual performance. This result is consistent with laboratory experiments where specific red/infrared wavelength ranges generated by LEDs have been used to improve visual function in animals and humans in a conserved manner [10, 14, 15]. But there are three critical differences from these earlier studies. First, we have simply changed environmental lighting in a free moving work environment. Second, we have obtained significant balanced improvements in both the protan and tritan range. Previously, exposure to restricted experimental 670nm resulted in improvements biased strongly in favour of only tritan function [10]. Hence, exposure to full spectrum lighting results in a balanced pattern of improvement in visual performance. Third, we have shown that improvements in visual function following incadescent are sustained for up to 6 weeks, and possibly beyond whereas they were confined to around 5 days when only restricted ranges of red light were used [10]. These three features change the way in which long wavelength light may be applied to improve human physiology by delivery in normal environments with lasting balance effects. These results are novel and may have public health implications.

Our study used 22 subjects, but was significant using both a before and after metric and also against an independent control group. They are also similar to group sizes in aspects of Shinhmar et al [10] (Figs. 2–5). However, future studies would clearly benefit from inclusion of a larger number of subjects.

The evolution of life on earth extends over 4 billion years, and that of humans over approximately 4–5 million years from the last common primate ancestor. This has all taken palce under sunlight that has a spectral range of approximately 300-2500nm, within which there has been an invariant balance between short and longer wavelengths. Human adoption of fire 1–2 million years ago supplemented sunlight as humans moved out of Africa as its spectrum is similar having a large infrared component.

Likewise, development of the Edison filament luminare, common until approximately 2000 had a spectrum similar to sunlight. However, around 2010 LED lighting with its highly restricted spectrum (350-650nm) and energy saving characteristics became common, resulting in a loss of infrared light in the built environment [1].

The physiology of life forms are adapted to natural environmental light in a highly conserved pattern across species. Light impacts on mitochondrial function, which is a key regulator of metabolism and ageing in animals. When the balance of short and long wavelengths is shifted there are consequences for mitochondria. When shorter wavelength exposure is dominant, as in LED lighting, mitochondrial function declines. Mitochondrial complex proteins are reduced and there is reduced ATP production [2, 3]. With reduced mitochondrial demand for glucose there is increased body weight and disruptions to serum cytokines [4]. Consequently, consistent with the mitochondrial theory of ageing there is an increased probability of cell/organism ageing and death [16]. It is suggested that this is partly due to 420-450nm light, dominant in LEDs, being absorbed by porphyrin and the subsequent production of oxygen singlets driving inflammation [3].

Conversely, exposure to longer wavelengths is associated with increased mitochondrial membrane potential and increased concentration of mitochondrial complex proteins that have declined with ageing and disease. This in turn is associated with elevated ATP, reduced inflammation and extended average lifespan and reduced inflammation [6, 8, 9, 17].

The retina has the greatest metabolic rate in the body and a high mitochondrial concentration [18]. Retinal metabolism declines with age, but this can be partly corrected with long wavelength light across species [14, 19]. In humans a 3 min 670nm exposure improves colour vision within 3h, which is sustained for almost a week [10]. But what the authors of this study did not appreciate was that this was within a population who worked and lived mainly under LED lighting that may have undermined their baseline measurements. Here, we made no attempt to control light exposures or subject movements as would occur in laboratory based experiments. Rather, our aim was to introduce wide spectrum long wavelengths into a work environment to improving human performance via mitochondrial manipulation.

There is considerable evidence that introduction of longer wavelengths impact systemically. Durieux et al [20] stated in relation to experiments in *C.elegans* that “ We find that mitochondrial perturbation in one tissue is perceived and acted upon by the mitochondrial stress response pathway in distal tissue” In mice there are significant distinct changes serum cytokine expression to exposures of both short and long wavelength light [4, 21]. Similarly, long wavelength exposures to the surface of the human body excluding the eyes significantly reduces blood glucose levels and increases oxygen consumption in humans. This is likely because mitochondrial upregulation will increase carbohydrate demand to support increased ATP production [11]. Other systemic impacts can be found and are clear in experimentally induced Parkinson’s in primates. Light targeted by implants focusing on the substantia nigra are effective in reducing symptoms [22], but so also are those that are directed at distal locations [23].

Single 3min 670nm exposures remain effective for about 5 days [10]. But we show that with a wider spectrum they remain effective for 6 weeks, although we did not find the end of the effect. Here it is worth considering potential mechanisms of action which remain subject of debate. Historically, improvements with red light were thought to be due to light absorption by cytochrome C in the respiratory chain [24]. However, positive effects are found in vitro in the absence of this. Consequently, it has been suggested that longer wavelengths reduce water viscosity around rotary ATP pumps allowing the rotor to increase speed [25], but this can not explain the sustained impacts of light exposure. However, a key feature of long wavelength light absorption is increased respiratory chain protein synthesis. These proteins are in flux throughout the day [26] and complex IV is upregulated following red light exposure [17]. Hence, while red light may initially increase rotor pump speed there rapidly follows an increase in protein synthesis to establish greater respiratory chain capacity. The life of these proteins may determine the length of effect.

Only thirteen polypeptides are made in mitochondrial protein synthesis. This probably slows with age and likely contributes to aged mitochondrial decline [16]. But critically, we do not know the speed of mitochondrial protein synthesis, the life of such proteins or the pace of their decline. We suggest that these may be key events in the length of the effects from light exposure.

Conclusions

LED lighting clearly has the ability to undermine visual performance probably via reduced mitochondrial function. As light induced changes in mitochondrial ability have been shown to have systemic impacts, the effect of LEDs revealed here may be wider than initially anticipated. Given the prevalence of LEDs, this may represent an important issue in public health and clinical environments where changing in lighting patterns in appreciation of this point can have significant positive outcomes [27].

Methods

The Subjects: The study was conducted in accordance with the Declaration of Helsinki and approved by the UCL research ethics committee (16547/001). Each participant provided written informed consent prior to testing and data generated was anonymised. Subjects (N = 22) were of both sexes and between the ages of 23 and 65 years. All were healthy without visual or other health problems. Experimental subjects (N = 11) worked in the back of the Here East building on the north side, > 50m from what little light did manage to penetrate the entrance doors when open. They worked approximately 8 hours a day, 5 days a week exclusively under LED lighting. Control subjects (N = 11) worked in similar environments under LED lighting without direct sunlight.

The experimental location: Subjects worked at UCL Here East, a media and innovation complex located in East London (London E15 2GW), originally built as a press and broadcast centre for the London 2012 Olympics and subsequently repurposed as a campus. UCL Here East occupies part of the Broadcast Centre, taking up the ground and first floor of unit B. The footprint of the building is deep, with daylight

only able enter through the glazing at the front of the building. This glazing uses an infrared blocking film, which can be revealed using infrared photography.

A Canon 500D digital camera was modified to replace the infrared blocking layer with clear glass that passes infrared wavelengths. This was used in conjunction with filters that block visible and infrared wavelengths to explore the presence and absence of infrared light in the experimental environment. Spectral measurements were made with *two* spectrophotometers (Ocean Optics SR-6XR250-50 and FLAME-NIR) with optic fibre and cosine correctors were used to collect the incandescent spectra in the shorter (black) and longer (red) wavelengths.

Incandescent desk lighting was introduced into the work environment using desk lamps with 60W clear Edison bulbs (Polaris UK) placed on work benches. The layout of the supplementary lighting is shown for illustration in Fig. 4. All subjects had worked in this LED-lit environment for more than 2 years. Desk lamps with incandescent bulbs were introduced onto the benches where experimental subjects spent the majority of their time. They were given the incandescent lighting for 2 weeks and, while they spend the majority of their time working near these lights, they were free to move around and leave their desks as they wished. This light showed a high degree of reflectance from the work surfaces.

Colour contrast testing: All subjects were tested for colour contrast ability using ChromaTest prior to the introduction of incandescent lighting and then again 2 weeks later. The incandescent lighting was then removed and subjects retested at 4 and 6 weeks. Hence, this element of the experiment was a before and after design which avoids between subject variability. However, there was also a separate control group (N = 11) composed of subjects that worked under LED lighting similar to those in the experimental group.

ChromaTests is a sensitive measure of colour contrast detection of letters presented in a random order against a noisy visual background in either tritan (blue) or protan (red) visual axes [10]. If subjects correctly identify a letter its contrast is reduced in the next presentation of a letter. Likewise, if they fail to correctly identify the letter, the contrast is increased. This is repeated until thresholds are determined in 5 identical repeated trials. This normally involved around 70–100 separate presentations in total. Subjects were given an initial trial before testing to avoid a learning effect. Initial presentations were at high colour contrast. No learning effects were noted in the study.

Declarations

Data availability statement

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Ethical statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the UCL research ethics committee (16547/001). Each participant provided written informed consent prior to testing and data generated was fully anonymised.

Declaration of competing interests

The authors have no competing interests.

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Author Contribution

Both authors designed the experiment, undertook all parts of the experimental procedure and also shared equally in the data analysis. Both authors also shared in the writing of the manuscript.

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Figures



Figure 1

Infrared photograph of the front of the Here East building (~800-1000 nm). The glazing reflects infrared light away, resulting in the mirror-like appearance of the windows. The photographer (EB) can be seen on right hand side of the reflection.



Figure 2

Infrared photograph (~800-1000nm) taken from inside the Here East building, showing infrared light only entering the building when the front doors are opened. The interior space appears otherwise completely dark as infrared light is not passed by the glazing.

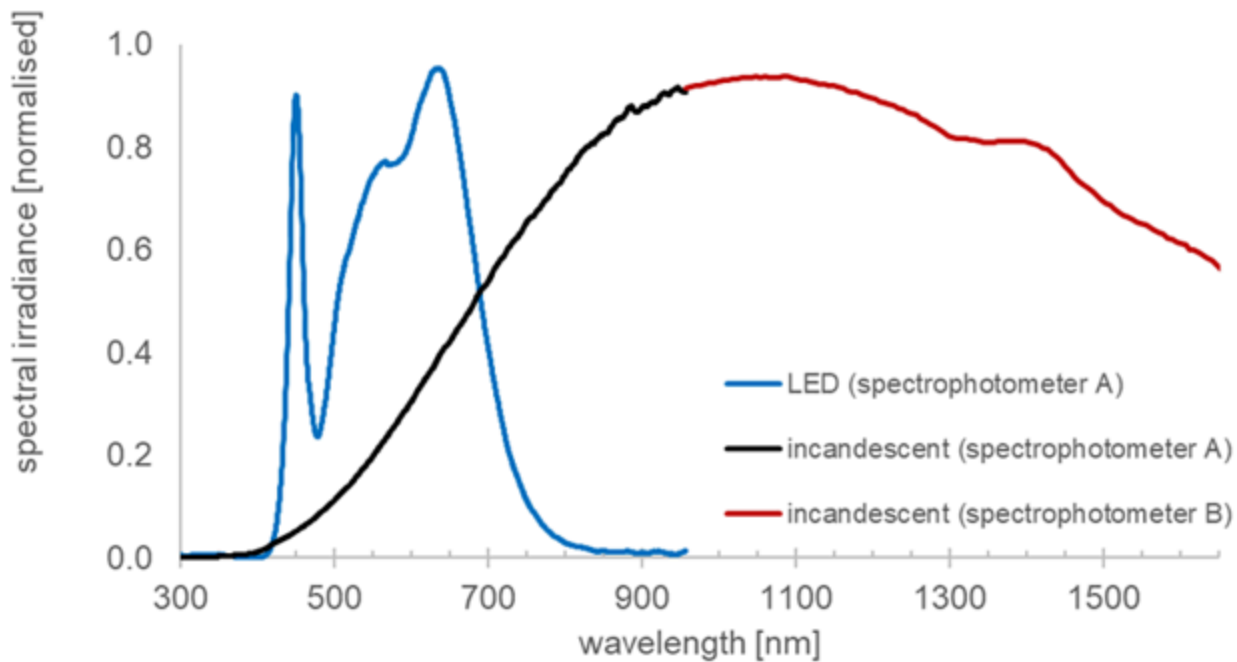


Figure 3

Spectral profiles of lighting. The light generated by the LEDs in the building is shown in blue and runs from approximately 350nm to 720nm, with a sharp peak at 450nm and a secondary shoulder between 500nm and approximately 700nm. The second spectra which is black and red is generated by a standard 60W incandescent desk lamp. This is similar to sunlight extending from approximately 350nm to >1700nm. The spectral profile of the incandescent is long wavelength shifted compared to the LED that lacks an extended infra-red component. The spectrum of this incandescent source extends beyond 2000nm. However, the spectrometers used to measure this lacked sensitivity at longer wavelengths. Individual spectrometers have limits to the spectral range they can cover, so two have been used here and their different wavelength ranges are represented by the black and the red parts of the curve.

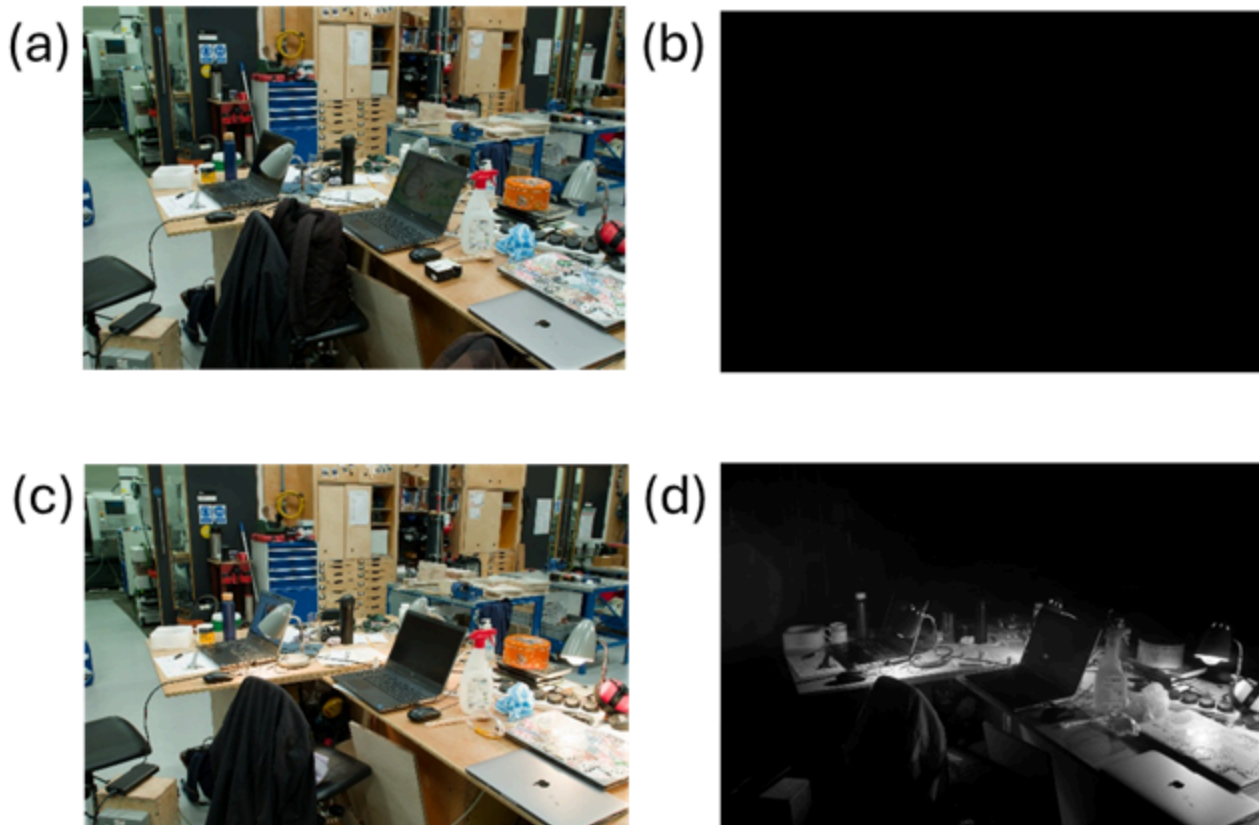


Figure 4

A series of photographs of the workshop area using the infrared sensitive camera with different filters. Photograph (a) shows the environment in visible light with the incandescent lighting off, and photograph (b) has the same with incandescent off but with infrared imaging. Photograph (c) shows the environment with the incandescent lighting on, and (d) shows the same with incandescent on and infrared imaging. Optical filters were used to isolate the visible and infrared parts of the spectrum respectively.

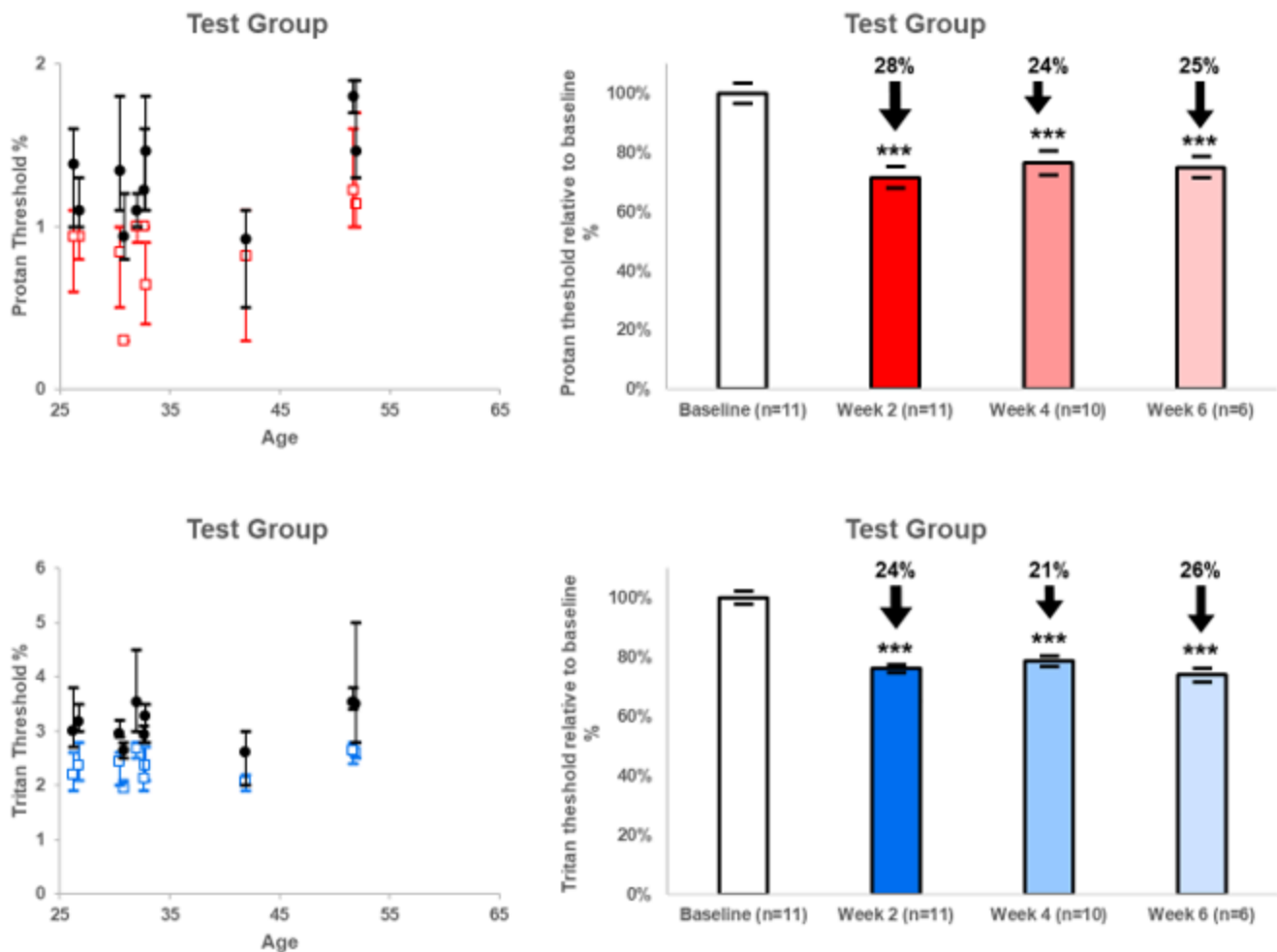


Figure 5

*Protan (a) and tritan (b) thresholds measurements following 2 weeks incandescent light. Left hand panels show data from individual subjects where the black circles are for baseline and the red squares are data following incandescent exposure for 2 weeks. In all cases the red post exposure data points are below the black demonstrating improved contrast. Right hand panels show the population change at 2, 4 and 6 weeks after the incandescent lighting was removed. Arrows and percentages show the decline in thresholds across subjects. The degree of reduction was consistently similar for protan and tritan unlike exposures using 670nm where improvements are biased to tritan and only lasted 5 days. This indicates that the wider spectrum of incandescent lighting is having a greater impact on improving vision and lasting longer than previously experienced. Statistical symbols: *** p less than 0.001. Error bars standard error of the mean.*

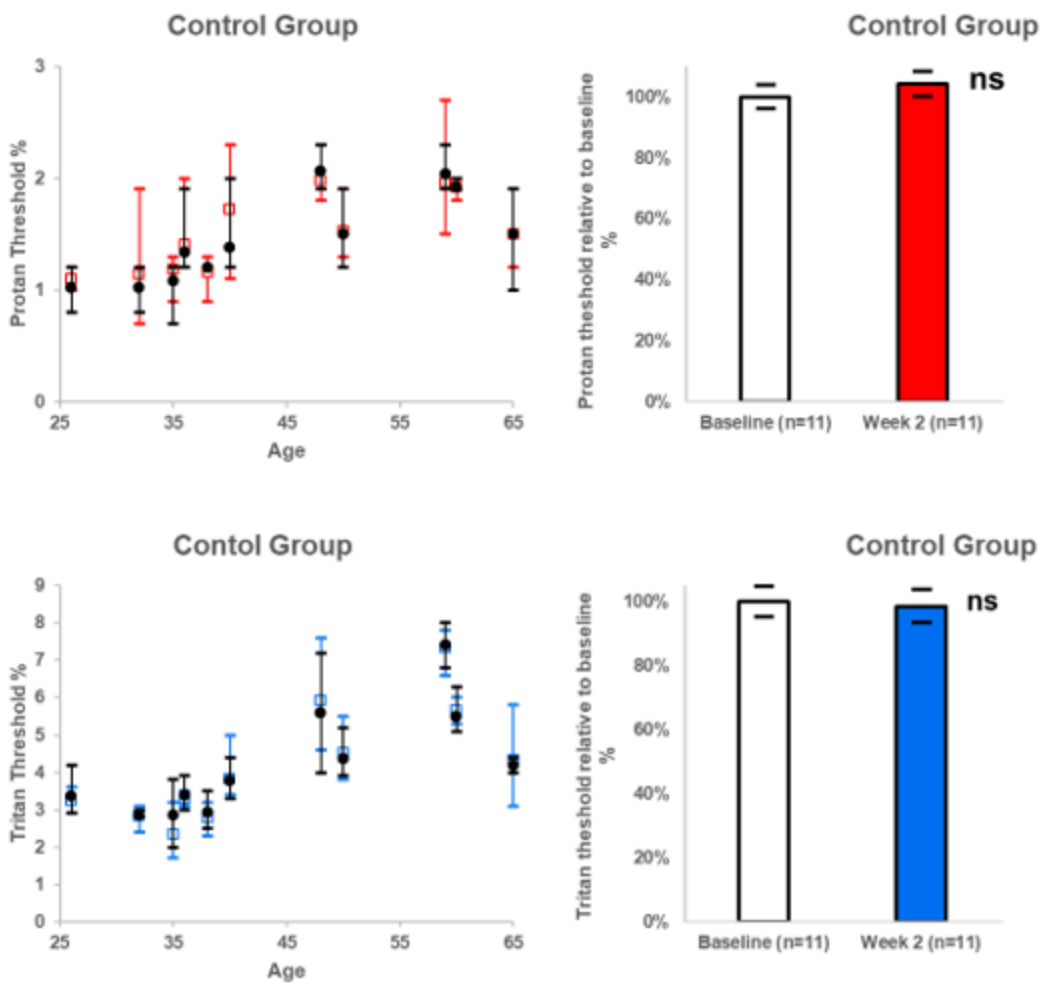


Figure 6

Subjects tested for colour contrast at baseline (a) and again at 2 weeks (b) as controls for those shown in Figure 5. Protan (a) and tritan (b) thresholds at baseline. Left hand panels show data from individual subjects where the black circles are for baseline and the red squares are data following incandescent exposure. In both the tritan and protan metrics there were no significant changes in this control group over the two week period. Abbreviations ns = Not significant. Error bars standard error of the mean.