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Light levels, refractive development, and myopia – A speculative review

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ABSTRACT

Recent epidemiological evidence in children indicates that time spent outdoors is protective against myopia. Studies in animal models (chick, macaque, tree shrew) have found that light levels (similar to being in the shade outdoors) that are mildly elevated compared to indoor levels, slow form-deprivation myopia and (in chick and tree shrew) lens-induced myopia. Normal chicks raised in low light levels (50 lux) with a circadian light on/off cycle often develop spontaneous myopia. We propose a model in which the ambient illuminance levels produce a continuum of effects on normal refractive development and the response to myopiagenic stimuli such that low light levels favor myopia development and elevated levels are protective. Among possible mechanisms, elevation of retinal dopamine activity seems the most likely. Inputs from intrinsically-photosensitive retinal ganglion cells (ipRGCs) at elevated light levels may be involved, providing additional activation of retinal dopaminergic pathways.

1. Introduction

Recent studies from numerous groups have reported that outdoor activity is protective against myopia development in children (Deng et al., 2010; Dirani et al., 2009; French et al., 2013; Guggenheim et al., 2012; Jones et al., 2007; Mutti et al., 2002; Rose et al., 2008a) and, in animal models of myopia, that elevated light levels slow the rate of myopia development (Ashby et al., 2009; Ashby and Schaeffel, 2010; Siegwart et al., 2012; Smith et al., 2012). These results raise the issue of the how ambient light levels may affect the emmetropization mechanism, including normal refractive development and the response to myopiagenic stimuli.

In comparison with illuminance levels outdoors, indoor lighting experienced by humans is typically less than 1000 lux and often much less – in the range of 100–500 lux. This, of course, is far less than the light levels experienced outdoors during the daytime (130,000 lux and above in direct sun on a clear day, about 15,000 lux in the shade). Indeed, these are the levels that presumably were experienced by terrestrial vertebrate eyes throughout the evolution of the primate line. Most terrestrial creatures develop in a visual environment that ranges from high photopic light levels outdoors during the day to mesopic levels at dawn and dusk (or inside buildings) and scotopic levels at night unless artificial lighting is provided. Rather than considering outdoor illuminance levels to be "high" or "bright" or "elevated," it is more appropriate to consider them as normal, and to consider "standard" indoor illuminance as low.

With the development of towns and cities, one may suppose that humans began to spend more time indoors, in lower-illuminance conditions; time spent indoors also appears to have increased with the development of indoor lighting and the development of non-agricultural indoor employment. Good visual acuity, needed for reading and other visual tasks that involve fine detail, is achieved with illuminances of approximately 100 lux–500 lux (Norton et al., 2002). Based at least in part on the increased costs involved in providing light levels above this point, indoor lighting for humans, and the lighting provided in the vivaria housing many of the animals used in studies of refractive development, are in this same illuminance range (Feldkaemper et al., 1999; Li and Howland, 2003; Morgan et al., 2004; Norton and McBrien, 1992; Schmid and Wildsoet, 1997; Smith, III et al., 2001) and, rarely, up to 1000 lux (Bitzer et al., 2000). The emerging reports of the protective effects of outdoor activity on myopia suggest that it is important to systematically explore the effect of illuminance levels above the low photopic levels experienced indoors.

In this review we suggest, as have Cohen et al. (2011, 2012) that the effects of illuminance on the emmetropization mechanism may form a continuum from scotopic and low photopic light levels, which foster the development myopic refractive errors, to the much higher illuminance levels experienced in the outdoors that affect

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refractive development, keeping eyes slightly hyperopic, and reduce the impact of myopiagenic stimuli. Indeed, in a 1999 paper on the effect of light levels on form-deprivation myopia in chicks, Feldkaemper et al. (1999) concluded, "Experiments show that the eye becomes more sensitive to image degradation at low light, the human eye may also be more prone to develop myopia if the light levels are low during extended periods of near work."

Although the amount of light reaching the retina is presumably the key factor, it is difficult to measure the $\mu W/cm^2$ of the many visible wavelengths that enter through the pupil and reach the retina. For convenience, illuminance (light falling on a surface) is a more easily measured quantity, indicating the amount of visible light (lumens) reaching an area of a surface (square meters) and corrected for the spectral sensitivity of humans: the lux. Illuminance levels from the sun on a clear day are approximately 130,000 lux (Birmingham, Alabama). Higher levels have also been reported (Dharani et al., 2012). In the shade on a sunny day, lux measured at the ground is typically 15,000–25,000 lux. Outdoors on a cloudy day it ranges from 10,000 to 40,000 lux. By comparison, indoor illuminance (100–500 lux) is very low.

Of course, most eyes are not pointed constantly toward the sky, but are aimed roughly parallel to the ground and mostly receive light reflected from objects. Light reaching the retina in this manner is lower, sometimes considerably so. Changes in pupil diameter also can alter the retinal illuminance by over 1 log unit. That said, the illuminance in lux can serve as an indicator of the upper limit of available light. This review will examine the relatively few studies that have varied the illuminance levels above and (in animal studies) slightly below standard indoor levels. Even though these indoor illuminance levels are, in an evolutionary sense, "low", they are the levels at which most human and animal observations have been made and therefore serve as a standard level. By comparison, outdoor illuminance levels and the levels used in a few animal studies are "elevated" and we will refer to them as such.

2. Human studies

2.1. Normal refractive development

The effects of illuminance on human refractive development occur against a background of changing refractive state in the months and years after birth. At birth, refractive state, measured with cycloplegia, is broadly distributed, ranging from low myopia (−1 to −4 D) to high hyperopia (up to 8 D) with a mean refraction of low (2 D) to moderate (3.5 D) hyperopia (Chen et al., 2011; Cook and Glasscock, 1951). This may reflect genetic factors that determine the location of the focal plane (corneal and lens curvatures and spacing) and the axial length before there is guidance from the emmetropization mechanism (Siegwart, Jr. and Norton, 2011). Very quickly, however, the refractive distribution narrows (Mayer et al., 2001; Mutti et al., 2005; Sorsby et al., 1957; Stenstrom and trans.Woolf, 1948). Eyes that are more hyperopic at 3 months of age grow axially more than emmetropic eyes, moving the retina toward the focal plane (Mutti et al., 2005). At some point in infancy or early childhood, the majority of eyes become nearly emmetropic, typically achieving a low hyperopia that is easily cleared with accommodation (Borchert et al., 2011; Gwiazda et al., 1993a; Howland et al., 1993; Multi-ethnic Pediatric Eye Disease Study, 2010). However, the degree of low hyperopia achieved has implications for subsequent refractive development. Having less than 0.5 D at about 6 years of age is a risk factor for subsequently developing myopia (Hirsch, 1964) as is having less than 0.75 D at about 8 years of age ("third grade") (Zadnik et al., 1999) or less than 0.75 D at 5 years of age for children with 2 myopic parents (Gwiazda et al., 2007). If, as suggested from animal studies (Section 3), exposure to outdoor light levels bias human refractive development toward remaining slightly more hyperopic, this hyperopia may provide a protective reserve against subsequent myopia development. Eyes that start to elongate and progress into myopia would start from a more hyperopic level, delaying the point at which they become myopic.

2.2. Myopia prevention

An important feature of being outdoors is that the illuminance levels are much higher than indoors. However, the number of hours spent outdoors among children and young adults seems quite variable depending on age, urban vs. rural location, ethnicity, and region of the world. Expressed as hours of outdoor activity per day (converted, in many cases, from hours per week presented in the reports) and based on responses to questionnaires, children living in Australia who are of European Caucasian ancestry have considerably more outdoor time (about 6 h per day) and lower myopia prevalence, compared with children of East Asian ancestry (∼4 h per day) (French et al., 2013). Children in rural suburbs of Beijing have been reported to have just over 2 h per day of outdoor activity whereas children in urban Beijing neighborhoods have about 1 h per day (Guo et al., 2013). In southwest England, Guggenheim et al. (2012) considered three or more hours per day outdoors in summertime as "high." Daily outdoor activity measures, also from questionnaires, have been reported to be as low as less than 0.5 h per day in Taiwan (Wu et al., 2010) and in Singapore (Rose et al., 2008b).

A growing number of human epidemiological studies in many countries have reported that time spent in outdoor activities is protective against myopia. Mutti et al. (2002) initially reported that myopia prevalence was inversely related to time spent participating in sports. Several subsequent studies also have shown that outdoor activity is inversely related to the development of myopia (Dirani et al., 2009; Guo et al., 2013; Jones et al., 2007; Jones-Jordan et al., 2011; Lee et al., 2013; Onal et al., 2007; Rose et al., 2008a; Sherwin et al., 2012b; Wu et al., 2010). Some studies have reported that it is the time outdoors, independent of physical activity, that is the important variable (Guggenheim et al., 2012; Rose et al., 2008a). Jones et al. (2007) found that children who spend more than 15 h per week (2.1 h per day) outdoors have only one-third the risk of becoming myopic as do children who spend less than 5 h per week (0.7 h per day) outdoors. In a review, Sherwin et al. (2012a) performed a meta-analysis on seven papers published between 2002 and 2010. They concluded that there was consistent evidence for a small reduction in the risk for being myopic related to the amount of time spent outside, such that each additional hour spent outside per week reduced the odds of being myopic by 2%. However, several studies have been published since then and, in agreement with Jones et al. (2007), suggest that the benefit of additional hours of daily outdoor exposure may be greater (French et al., 2013; Guggenheim et al., 2012). A separate issue is whether time spent outdoors also produces a small hyperopic shift in the refractions of emmetropic children (Rose et al., 2008a).

2.3. Myopia progression

In addition to being protective against becoming myopic, there is also evidence that outdoor activity may slow the progression of myopia in children who are already myopic, although some studies have not found a relationship (Jones-Jordan et al., 2012; Saw et al., 2000). Parssinen and Lyyra (1993) found that myopia progression was reduced in boys, but not girls, as the number of daily hours spent in outdoor activities increased. In a small intervention study in Hunan province, China (41 in intervention group, 39 in control group) myopia progression was compared over a 2-year period in myopic children aged 7–11 (Yi and Li, 2011). Based on