Impact of Macular Pigment on Visual Performance

James Loughman  
*Technological University Dublin*, james.loughman@tudublin.ie

Peter Davison  
*Technological University Dublin*, Peter.Davison@tudublin.ie

John Nolan  
*Waterford Institute of Technology*

Stephen Beatty  
*Waterford Institute of Technology*

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Evidenced is accumulating to suggest that macular pigment (MP), a component of the pigment epithelium, can change visual performance. Whether such short wavelength absorption influences vision is a major question. Whether MP has a role to play in visual performance is a topic of ongoing research.

To address the question of whether MP may influence visual performance, one must (a) initially consider the primary factors that affect performance, (b) outline the properties of MP that make it potentially useful in enhancing visual performance, (c) analyse existing evidence in support of MP, and (d) design experimental strategies that might more clearly elucidate the answers to the question of whether MP has a role to play.

**Visual performance**
Vision includes the capacity to detect objects against a contrasting background, to detect gaps between objects (such as in vernier tasks which provide one example of a hyperacuity), to recognise and identify objects, to perceive colour, to detect movement and to perceive depth among others. The capacity to recognise a small letter from a distance bears little relation to the capacity to differentiate colours or to detect a potential threat such as an oncoming vehicle in the peripheral field of view. Performance is critically dependent on illumination. The range of illumination we experience in the course of a day is vast. The visual system copes with the huge range of luminances by adapting to the prevailing conditions and can function through a staggering luminance range of nearly 10 log units. Although adaptation facilitates performance over a wide range of ambient illumination levels, this does not mean that we see equally well at all levels. Under dim conditions the eyes are very sensitive and can detect subtle changes in luminance but acuity for pattern details and colour discrimination are poor.

Shaler (1937) has explored the relationship between illumination and gratings. Converting his findings to Snellen equivalent, daylight (photopic) performance of 6/3 reduces to 6/90 under dim conditions, a 30-fold reduction. Threshold visibility, colour appearance and visual acuity all vary dramatically at different illumination levels, and these visual parameters change over the time-course of light and dark adaptation. No single test or testing condition can therefore define visual performance.

It is also important to remember that when describing visual processes, vision also involves the processes leading to perception. The visual system employs numerous anatomical and physiological strategies including lateral interactions between cells, specific receptive field organisation, spatial retinotopic organisation in retinal and non-retinal areas of the pathway, colour opponency and parallel visual pathways among others in order to achieve an instantaneous (stable and constant), yet coherent and highly detailed perception of the outside world and our position within it. Such image processing is not exclusive to the brain but extends throughout the visual pathway beginning at the retina. The eyes and brain are thus inextricably linked with the visual universe. The eyes actively record the form, colour and movements of the world, and the brain moulds these raw perceptions into recognisable patterns. The retina essentially acts as a spatial, temporal and spectral filter of patterns of light striking its surface. Its anatomical structure and the functional properties of individual cells determine the type of information extracted from a visual scene and delivered to the brain, namely the retina analyses and controls what information is delivered to the brain.

**Specialisation of the macula**
The macula, which comprises less than 4 per cent of the total retinal area, accounts for almost all of our useful photopic vision. The macula is an area located in the retina that is responsible for central vision and fine detail. The macula is involved in tasks that require high visual acuity, such as reading, driving, and recognizing faces. The macula contains photoreceptors that are more sensitive to light than those in other parts of the retina. This allows for clearer and more detailed vision in the central part of the field of view. The macula is also responsible for color vision, as it contains photoreceptors that are sensitive to different wavelengths of light. This allows us to see colors in the central part of the visual field. The macula is an area of the retina that is responsible for high visual acuity and color vision. It is involved in tasks that require clear vision, such as reading and driving.

James Loughmann, Peter Davidson, John Nolan and Stephen Beatty describe the latest research into the macula and visual performance and how macular pigments may affect vision. C7230, one general CET point, suitable for optometrists and dispensing opticians.
vision. Several distinctive anatomical and neural adaptations facilitate such high level visual performance. These include:

- Cone density reaches a peak at the centre of the macula (fovea) which intersects the line of sight. Cone density exceeds rod density only at the lower part of the foveal slope reaching a maximum at the base of the fovea (foveola) where cone density is more than three times the density at the base of the foveal slope (Curcio et al. 1990). Rods, ganglion cells and all inner nuclear layer neurons are absent from the foveola so that only here is light directly incident on photoreceptors (elsewhere light must traverse the various retinal cells and layers to reach photoreceptors).

- Midget pathways arising from these foveal cones dominate. Such parvocellular midget pathways are tuned to high spatial frequencies (allowing high acuity) and also exhibit colour opponency.

- Such midget pathways are distinctive in the absence of convergence of photoreceptor signals onto bipolar and ganglion cells. Absent or reduced convergence of information preserves the information gathered at the fovea for delivery to the visual cortex. This difference between foveal and extra-foveal processing generates a hierarchy in the importance of retinal information.

- The retinal hierarchy afforded to foveal cone-mediated vision extends back to the visual cortex where the central retinal pathways have by far the greatest representation (Wong and Sharpe, 1999; Horton and Hoyt, 1991). Having outlined those anatomical and neural factors central to primates’ capacity for high acuity vision, it is now important to consider the potential role of macular pigment in further enhancing visual performance. In order to do so, it is essential to characterise (a) the optical limitations that might restrict visual performance (in particular chromatic aberration and light scatter) and (b) the properties of macular pigment that might serve to lessen the effect of such limitations and thereby facilitate improved performance.

### Optical limitations of the eye

Monochromatic aberrations and diffraction limit the image quality produced by the eye so that the image is not a high quality representation of the object. While there is significant ocular and neural correction for and adaptation to such image defects, macular pigment has no role in altering their effects.

### Chromatic aberration

Chromatic aberration, comprising both longitudinal (LCA) and transverse (TCA) components, has been cited as possibly the most significant aberration affecting visual quality (Howarth and Bradley, 1986). LCA creates up to two dioptres of wavelength-dependent optical defocus (Figure 1).

The effect of LCA across wavelength in terms of blur is non-linear — that is shorter wavelengths are significantly more blurred than longer wavelengths. For example, for a typical eye focused at 555nm, light at 460nm suffers 1.2D myopic defocus, while the equivalent long wavelength of 650nm is only 0.50D out of focus (Howarth and Bradley, 1986). This serves to create a purple blur circle haze around the focussed ‘green’ component. The ultimate effect of such optical aberrations, and in particular LCA, is that capacity limits are somewhat reduced so that the anatomical limits of acuity based on foveal cone diameter (30 secs arc—equivalent to 6/3), are seldom achieved even by healthy normal individuals.

### Light scatter

If one looks up to the sky on a bright, cloudless sunny day, one could be fooled into thinking that the sun’s rays traverse an unobstructed path to the eye. Furthermore, one could certainly not imagine the quality of the light visible was being degraded as it traversed the seemingly clear sky, even in the most remote countryside locations far from the smog-filled cityscapes on its way to the eye. The fact that the sky is blue is testament to the impact of the process of light scatter, whereby, particle matter including haze aerosols, fog, and cloud, abstracts and re-radiates energy from light incident upon it.

Wooten and Hammond (2002), in an excellent review of the importance of light scatter to the ‘visibility’ of objects, eloquently describe why light scatter, especially that induced by haze aerosols ‘critically determines how far one can see and how well details can be resolved’, so that, aside from the optical and neural limits, ‘scatter in the haze aerosols is the primary determinant of visual discrimination and range in the outdoors’.

The question therefore arises, what effect does light scatter have on visual performance? It is a good question. On a clear day one can see for miles despite the effects of scatter. However, it has been shown that compensation for the effects of light scatter, such as could reasonably be achieved by increasing the density of macular pigment could increase the visibility and discriminability of targets in natural settings (Wooten and Hammond, 2002). Tackling the question from another perspective, the problems caused by scatter, while not consciously experienced by some people, do become a significant symptom of which many of our patients complain. Typical examples include those with light-coloured irides, cataract, corneal abnormalities and infections, and post-laser refractive patients among others. Scatter, therefore, does have an adverse effect on the visual experience of normals and those with ocular abnormalities alike, and therefore any means to reduce the effects of scatter can only be of benefit. So now the question arises, what are the properties of MP that might allow it to improve visual performance in light of the limiting factors outlined above?

### Optical properties of MP

The ‘optical’ hypotheses of MP were discussed in significant detail initially by Reading and Weale (1974), and later by Nussbaum et al (1981), and may be related to at least one of the following properties: MP may enhance visual acuity by reducing chromatic aberration; MP may reduce visual discomfort by attenuation of glare and dazzle; MP may facilitate enhancement of detail by the absorption of ‘blue haze’; MP may enhance visual contrast.

MP has the capacity to achieve the above optical effects because of its optical properties and its location in the retina.

The term macula is actually derived from the presence of the xanthophyll pigments, lutein (L) and zeaxanthin (Z), at the central region of the retina, which give rise to the appearance of a yellow spot ‘macula lutea’ when viewed under red-free light. The yellow nature of MP is such that it selectively absorbs blue-green incident light, with maximum absorption circa 460nm and little or no absorption above 530nm (Bone et al., 1992). Given that, (a) the peak retinal spectral sensitivity lies at 555nm, (b) the percentage of blue (short wavelength sensitive) cones compared to that of...
red (long wavelength sensitive) and green (medium wavelength sensitive) cones is vastly reduced and (c) there is a complete absence of blue cones from the region of maximal visual performance, the foveola, MP it seems therefore removes that component of light which has least benefit from a performance perspective.

Two aspects of MP location within the retina are also central to the assumption that it has a role to play in visual performance. Firstly, although MP is diffusely distributed throughout the retina and other ocular structures (Davies and Morland, 2004), it is mostly concentrated at the macula and remains optically undetectable elsewhere. Secondly, and importantly, MP is located at a pre-recepto- torial level, so such absorptions are made prior to light stimulation of underlying photoreceptors, thereby altering the spectral distribution of light incident on such photoreceptors.

Given its short wavelength absorption characteristics and central, pre-recepto- torial location, MP retains ideal properties to improve visual performance. Blue light absorption attenuates the more disadvan-
tageous short wavelength component of LCA. Retinal image quality is, there- fore, improved and visual performance across the full contrast range is theoreti- cally more refined. As MP absorption overlaps with that of rhodopsin, MP may reduce rod signal effectiveness in the mesopic range, and thus extend the usefulness of cone-mediated vision into the mesopic range (Kvansakul et al., 2006).

In addition, blue light absorption has the benefit of improving target contrast by selectively reducing the scattered blue light in the background. Reduced LCA and reduced scatter effects associated with MP therefore have the combined potential to improve visual acuity and target visibility (Wooten and Hammond, 2002).

The higher energy and retinal irradi- ance associated with shorter wavelengths also merits consideration. Bright light, which interferes with the quality of visual perception is termed glare, of which there are numerous types. Glare is a frequent complaint among persons with advanced age, retinal disease, and cataract, as well as at any age in some individuals without obvious reasons for predisposition. In high luminance or high contrast situations, where glare and dazzle are maximal, MP absorp- tion of blue light removes the highest energy light component, reduces retinal irradiance and may therefore have the combined benefits of minimising the impact of glare on performance and increasing the threshold for photopho-
primary research focus for the effects of L and Z supplementation. Observations including relative preservation of blue cones centrally compared to perifoveally (Shaban et al., 2002) and geographic atrophy in AMD typically appearing initially in the perifovea where MP density is lowest, lend weight to the assertion that MP protects visual function at the fovea. Since the original findings of the Eye Disease Case-Control Study Group of a 60 per cent reduced risk of developing AMD associated with high intakes of L and Z (Seddon et al., 1994), numerous investigators have explored the relationship between L and Z in the diet or blood and AMD. With a couple of exceptions (outlined below), empirical studies on the effects of L and Z supplementation on AMD progression, in terms of visual function, focus mainly (and understandably) on the capacity of L and Z supplementation to halt progression of functional loss, not on the potential to improve visual function in established AMD. Results have been somewhat variable, with some studies showing a beneficial effect of higher intakes of L or Z (Mares-Periman et al., 2001; Snellen et al., 2002; Gale et al., 2003), while others have not (VandenLangenberg et al., 1998; Flood et al., 2002; Cho et al., 2004).

Falsini et al. (2003) measured the effect of L supplementation on central electrophysiological function in patients with AMD and found a significant increase in focal ERG amplitude after six months’ supplementation, followed by decreased amplitude back to baseline following cessation. Curiously, they did not record MPOD so their conclusions are somewhat limited. The lutein antioxidant supplementation trial study provides the most intriguing findings in relation to visual function among AMD patients. Patients supplemented with L or L plus other antioxidants achieved improved visual function outcomes attributable to increased MPOD measures. Snellen-equivalent acuity improved by 5.4 letters in the L group and by 3.5 letters in the L plus antioxidant group (Richer et al., 2004). Improvements were also seen in contrast sensitivity and subjectively on Amsler grid and glare recovery. Placebo control subjects achieved no such improvements.

(3) Other conditions
Olmedilla et al. (2003) explored the possibility that L supplementation might influence visual function in patients with age-related cataract. Visual performance was evaluated through visual acuity and glare sensitivity measures. This randomised, placebo-controlled study revealed significant improvements in visual acuity and glare sensitivity associated with increased blood serum L levels after supplementation. No such improvements were achieved in placebo controls or in those supplemented with Δ-tocopherol. The authors postulate that such improvements are not the consequence of any change in the crystalline lens, but from possibly improved retinal integrity.

Cystic fibrosis (CF) is a condition associated with deficient carotenoid absorption due to pancreatic insufficiency. Carotenoid concentrations, including the MP components, are almost uniformly low in CF patients. Beatty et al. (2004) have shown that ocular MP levels vary with blood serum levels and therefore MP levels can be assumed to be low in cases of CF. Schupp et al. (2004) assessed visual performance in 10 such CF patients. Serum L and Z concentrations, as well as MPOD in the eye were significantly reduced in CF patients to less than half the levels of control subjects. Visual performance on contrast sensitivity, colour discrimination and multifocal ERG amplitudes, although better in the control group, were, however, not statistically significantly different between the two groups.

Normal population studies

(1) Photophobia and glare
Photophobia is a global phenomenon experienced under sudden and extreme changes of illumination from dark to light, for example turning on the bedroom lights at night. However, under normal daylight conditions, the experience of photophobia is somewhat more variable. Numerous clinical conditions cause photophobia, and even in the absence of detectable disease, clinicians are often presented with patients whose primary complaint is of periodic or persistent hyper-sensitivity to bright light. Given its absorption characteristics, MP and in particular the density of MP may have a central role in determining the individual photophobia threshold.

Stringham et al. (2003) explored the effect of the spectral composition of a target on visual discomfort. They showed that while there was a positive relationship between wavelength and the energy needed to produce photophobia for wavelengths between 520nm and 640nm, at shorter wavelengths there was a notch centred at 460nm. MPOD differences among the subjects also appeared to account for differences in photophobic sensitivity below 520nm.

Such findings led to a subsequent study to test the direct relationship between MP and photophobia (Wenzel et al., 2006). This two-part experiment explored the relationship between baseline MPOD levels and photophobia thresholds, as well as the effect of increasing MPOD on such thresholds. They found a linear relationship between baseline MPOD and photophobia — that is individuals with higher MPOD were less susceptible to photophobia.

Furthermore, increasing MPOD over a 12-week period appeared to confer a predictable improvement in photophobia threshold increasing the amount of light necessary to induce visual discom-
fort for short wavelength targets. Recent data from Hammond et al – presented at ‘Coloured filters in the Eye’ at City University in November last year – found that both photosensory recovery and grating visibility under veiling conditions were strongly related to MP density, supporting the photopho-
fia findings outlined above.

(2) Acuity and contrast sensitivity
Engles et al (2007) have evaluated the ‘acuity hypothesis’, exploring the relationship between gap acuity, vernier acuity and MPOD under photopic conditions. They report that neither gap acuity nor vernier acuity were signifi-
cantly correlated with MPOD and conclude that their ‘data suggest that the predictions of the acuity hypoth-
hesis do not hold’. Numerous limitations (some recognised by the authors) in their study design, however, mean that such a conclusion goes far beyond the scope of their findings and cannot be justi-
fied. The acuity findings, however, do suggest that the contribution of MP to visual performance may be less impor-
tant for the aspects of photopic vision to which the system is most highly tuned. Retinal image quality is adversely affected in mesopic conditions as a result of increased aberrations and scattered light. Visual performance is typically much more variable in the mesopic range, where the influence of rods on spatio-temporal vision pre-dominates and results in reduced contrast acuity.

As rods are sensitive to blue light (peak rod sensitivity lies around 498nm in the blue-green part of the spectrum), Kivansakul et al (2006) have postulated that blue-light absorption may reduce rod signals and thereby extend the superior characteristics of cone-dominated vision lower into the mesopic range. They investigated the effect of increasing MPOD through L and Z supple-
mentation on contrast acuity and found that regardless of whether groups were supplemented with L, with Z, or with a combination of the two, there was a trend towards improved performance. The improvement was statisti-
cally significant for the L group so that supplementation has now been shown to enhance visual performance at low illumination levels.

Conclusion
Visual performance in the normal human observer is less than ideal. Evidence exists that once chromatic and monochromatic aberrations are removed, visual performance improves (Yoon and Williams, 2002). As such numerous strategies exist which aim to improve visual performance.

Wavefront-guided laser refractive eye surgery, wavefront-guided spectacle lenses, blue-filtering IOL implants, blue-
filtering contact lenses and blue-filtering spectacle lenses all attempt to improve or optimise visual performance. All such techniques, however, are designed primarily for persons with pre-existing ocular abnormality or disease. It is generally accepted and has been shown that age results in a decline in visual function for a wide variety of reasons. MP has been shown to preserve visual function in age-related retinal disease such as AMD presumably by protecting remaining foveal cones. By preserving foveal cones and possibly crystalline lens clarity MP may thus retard functional losses into old age.

To summarise, MP has ideal proper-
ties in terms of location and spectral absorbance to have a beneficial effect on visual performance. Longer life spans, increased exposure to short wavelength blue light (ancestors had no blue light exposure after dark), increased effects of scatter from expanding smog and haze, modern visual requirements and the explosion in the incidence of AMD heightens the importance of both improv-
ing visual performance in the short term, and preserving such performance in the long term.

Definitive supporting evidence, however, has not been provided with sufficient clarity and depth to fully describe the role of MP in vision, neither in the short term nor over time.

Interpretation of the findings in the studies cited above should therefore be approached with full appreciation of the design flaws, insufficient visual performance evaluation, and in partic-
ular the small sample sizes used. High quality emergent research with sufficient subject numbers tracked longitudinally is now required to address the issue more completely.

● J Loughman and PA Davison are from the Optometry Department, Dublin Institute of Technology and John Nolan and Stephen Beattie are based at the Macular Pigment Research Group, Waterford Institute of Technology.