Influence of the dietary carotenoids lutein and zeaxanthin on visual performance: application to baseball[1–3]

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ABSTRACT

Macular pigment (MP) is composed of the yellow, blue-absorbing carotenoids lutein and zeaxanthin. Although distributed throughout the visual system, MP is heavily concentrated in the central retinal area (eg, screening the foveal cones). Because light must pass through MP before reaching the receptors, it filters significant amounts of short-wave energy. Individual variation in peak absorbance is large and ranges from 0.0 to 1.6 optical density units depending largely on dietary intake. Several important functions of MP have been proposed. MP may serve to protect the retina from damage by absorbing actinic short-wave light (analogous to internal sunglasses) or by inactivating highly reactive free radicals and oxygen triplicates that are the by-product of light-driven cellular activity. MP may also serve, as proposed more than a century ago, to improve the retinal image through optical mechanisms. Recent data suggest that the MP carotenoids reduce glare discomfort and disability, shorten photostress recovery times, enhance chromatic contrast, and increase visual range (how far one can see in the distance). Lutein and zeaxanthin within the brain might also increase temporal processing speeds. This article reviews the influences of MP on visual function by exploring the implications of these visual improvements for baseball players. *Am J Clin Nutr* 2012;96(suppl):1207S–13S.

INTRODUCTION

Visual performance has always been an important issue in professional sports in which a small edge can translate to large gains (1), and this is particularly true of baseball. It is rarely the case, however, that baseball players are screened for visual capabilities that relate more directly to performance on the field. Ecologic measures of the visual function of baseball players can be difficult and often involves complex laboratory equipment not available to most teams. The need to know this information may be important, however, because many of these visual capabilities can potentially be improved. In fact, recent data have shown that a number of visual abilities that would be relevant to athletic performance may be amenable to large improvements simply by focused changes in diet or through supplementation. For example, glare discomfort, glare disability, photostress recovery, chromatic contrast, visible range, and temporal processing speed are all likely to be important to baseball players. Some, if not all, of these visual capabilities can be enhanced by increased intake of the dietary carotenoids lutein and zeaxanthin (2–8). These dietary pigments are found throughout the tissues of the eye (9) and brain (10) and are strongly concentrated in the central macular portion of the retina [referred to as macular pigment (MP); 11]. It is possible that many baseball players have very low concentrations of these pigments because of their relatively poor diets, which typically do not include enough carotenoid-rich fruit and vegetables (1, 12). A poor diet for baseball players would be consistent with the overall poor quality of the American diet in general (∼1–2 mg lutein and zeaxanthin/d; in comparison, a cup of spinach contains ∼10–12 mg lutein and zeaxanthin; 13). Hence, it is possible that some athletes might garner large improvements in performance by the relatively simple (and in fact healthy) expedient of increasing their intake of carotenoid-rich foods and/or supplementing purified forms of these antioxidant pigments.

VISUAL PERFORMANCE OF BASEBALL PLAYERS

As a general rule, baseball players tend to have very good static visual acuity. Optimal acuity in baseball players is probably due to self-selection—ie, if they had poor vision they probably would not have been initially drawn to sports nor would they have succeeded. This is probably why baseball players also tend to have good dynamic acuity as well (14, 15). The static and dynamic acuity of baseball players has been carefully studied in controlled laboratory settings [commonly used tests are contrast sensitivity function (CSF), Snellen acuity, and other similar tests (*see* references 14 and 16)]. For example, Rouse et al (15) measured dynamic acuity by using Landolt "Cs" (one sees the letter C and indicates the direction of the gap) that move on a projection screen. They found that the dynamic visual acuity of college baseball players was, on average, ∼15% better than a matched control group of college students.

Optimal visual performance, however, is more than simply optimal static and dynamic acuity. Many other aspects of the visual environment influence visual performance in the real world. In fact, measures of vision that match more closely the actual performance of players probably help to explain part of the differences seen in individual players (ie, such measures may more accurately predict actual performance). Classé et al (17),

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for example, found a relation between visual reaction time and batting skill but no relation between visual reaction time and skill at pitching or fielding. As a general rule, the more ecologically valid a measure is (the more closely it matches what it attempts to describe), the more likely it is to predict real-world performance.

Ecologic validity is a term that is often used to describe how behavior measured in a laboratory setting translates to behavior measured in a multitude of real-world environments. As noted by Owsley and Sloane (18) in an early study that addressed the ecologic validity of acuity and CSF, "A major assumption underlying the use of contrast sensitivity testing is that it predicts whether a patient has difficulty seeing objects encountered in everyday life. However, there has been no large-scale attempt to evaluate whether this putative relationship actually exists."

To test this assumption, Owsley and Sloane measured Snellen acuity and the CSF of 93 subjects (aged 20–77 y). These measures were then compared with target images (faces, road signs, and other objects) that were placed on back-illuminated slides. These slides were placed in an optical system that allowed the contrast within the object to be varied. These authors found that Snellen acuity did not predict threshold identification of these "real-world targets." CSF did predict real-world performance but explained only ∼25–40% of the variance.

Thus, to accurately predict the visual performance of baseball players, one must consider what factors influence vision under the type of conditions players are likely to encounter (examples of factors are shown in **Figure 1**). Games usually occur outdoors, and there are many factors (other than just refractive state) that contribute to vision in the external environment. When considering field conditions, some issues are immediately apparent. For example, looking into the bright sun (very broad spectrum light) and intense overhead lights (often xenon-based, also broad spectrum) can cause visual loss due to light scattering within the ocular media. This light scattering can cause a player to lose sight of a visual target (such as a baseball). The conditions that promote glare occur when individuals are exposed to a light source, either direct or indirect, that is in excess of their adaptive state. Such light can cause both glare discomfort and disability (a loss in the visibility of low-contrast objects). All light is not equivalent in its ability to create discomfort or disability. All things being equal, light in the short-wave region of the visible spectrum, blue light, appears to be particularly deleterious (3). Light exposure that is sufficiently intense can actually be quite "blinding" (termed *photostress*), especially if a significant proportion of photopigment is bleached.

Efforts to solve the problem of visual loss due to intense-light conditions have a long history in athletics. A baseball glove was invented some years ago (US patent no. 4453272), for instance, that was designed to deal with the large problem of glare on fielding. As noted in the patent application, "A baseball glove according to this invention comprises an antiglare web attached between sheaths thereof for the thumb and the index finger. A player can watch a fly by peering through the web without being hindered by the glare of sunlight or stadium lights of illumination."

Baseball caps were invented to shield a player's eyes from the sun or the powerful lights that are used to illuminate the field at night time. Eye black (a dark grease placed under the eye) is also used to reduce glare from sunlight or stadium lights (19), which can interfere with player performance (although tinted contact lenses work better for this purpose; 20). Some of the environmental factors that must be considered during evaluation of the visual performance of baseball players under ecologically valid conditions are outlined in Figure 1.

Intense light that scatters in the ocular media is just one way that visual performance is hindered in the real-world environment. In some cases, ambient lighting in not overly intense, but there is very poor contrast between a target (such as a ball) and its background or surround. Visual contrast is often defined by using the Weber fraction, in which contrast equals the increment or decrement in the luminance of a target divided by the luminance of a uniform surrounding field (20). The visual system highlights these small contrast differences through numerous neural mechanisms such as lateral inhibition. Contrast is very important for the ability to detect

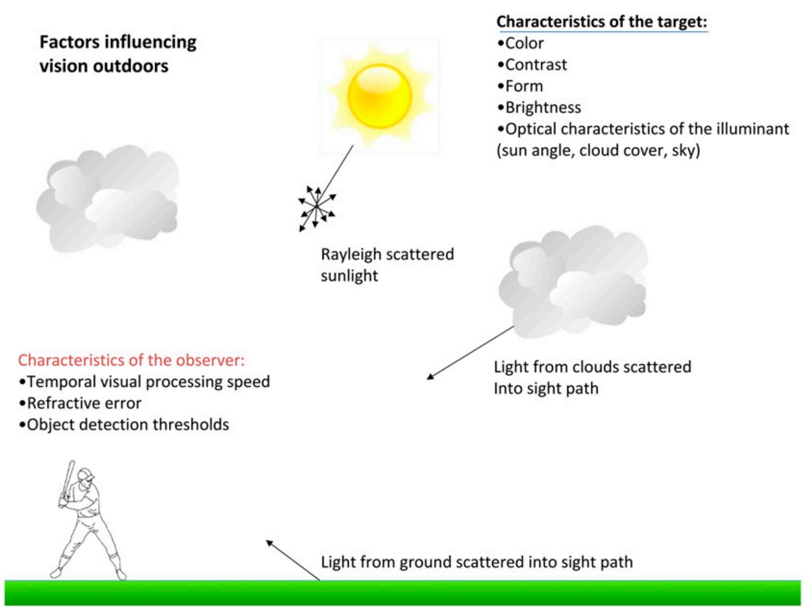

FIGURE 1. Factors that influence vision outdoors.

many objects in visual space. The trajectory of a batted ball, for instance, is such that a fielder is often viewing a ball against a background of the blue sky or a patterned dome reflecting the broadband light of overhead luminants. There are numerous factors (also not well described by standard acuity assessments) that influence the contrast of an object with its background in real-world conditions (*see* Figure 1). For example, the earth's atmosphere through which we view objects almost always contains small, suspended particles from both natural and manmade sources. This haze aerosol, as it is called, scatters short-wave light more than other wavelengths and results in a bluish veiling luminance. *Blue haze*, as it is sometimes termed, is a major factor that degrades visibility—ie, how well and how far we can see targets in the outdoors [*see* the analysis by Wooten and Hammond (2)].

With respect to visibility, contrast, and glare disability, it appears that short-wave (blue) light is particularly pernicious (2, 7, 8). Light scatter in the atmosphere is wavelength dependent, being strongest at short wavelengths (λ^{-4}, Rayleigh scatter)

The excessive scattering of short-wave light also manifests when analyzing haze. It is easily observable that distant objects, such as the features of mountain sides, have a distinctively bluish appearance (eg, "purple mountains' majesty"). Hydrocarbon particles released by vegetation (such as terpenes) react with ozone creating blue haze that limits vision in the distance. The peak energy of both blue haze and skylight is 460 nm (coincident with the peak absorbance of MP; *see* **Figure 2**).

A somewhat opposite effect occurs for objects that are in our line of sight. Short-wave light is scattered out of the optical path, and the wavelength composition of the target is shifted toward the longer wavelengths. Visibility can be easily quantified. It is, essentially, how far (when all conditions are equal) one can see in the distance (22). If, for example, a player can see a falling ball sooner (ie, visual range is increased), the probability of a successful catch is increased (*see* **Figure 3**).

Glare and contrast issues are important and independent predictors of real-world visual performance (23). Nonetheless, they are essentially static. As discussed earlier, however, a complete visual assessment must also consider the dynamic visual and psychomotor needs of baseball players. For example,

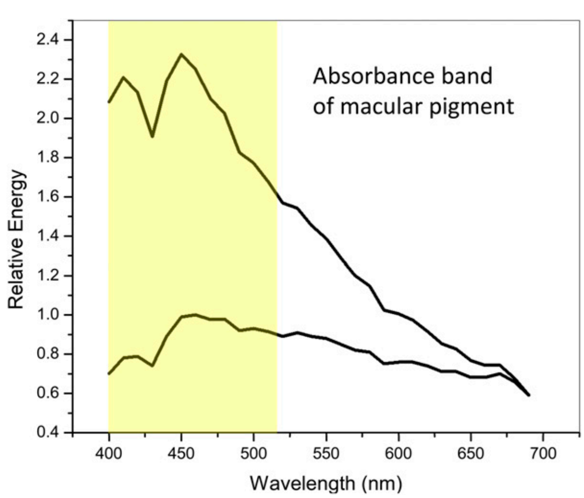

FIGURE 2. Sunlight (D6500; lower curve) and "blue haze" (upper curve) from tabular data provided in Wyszecki and Stiles (21). Note that both curves peak at 460 nm, which is the peak absorption of macular pigment (shown with the dashed blue line).

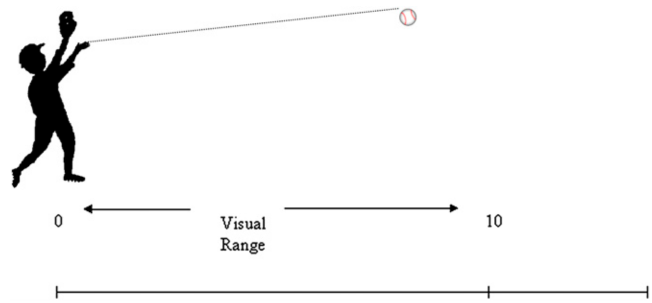

FIGURE 3. Visibility refers to how far an individual can see and the distinctness with which objects can be distinguished from their surroundings. Light scatter is the primary extrinsic determinant of visual discrimination and range in the outdoors. The more distant an object, the lighter it also appears, until it cannot be discriminated from the surrounding horizon. The increasing haziness of distant objects is referred to as "aerial prospective" and is sometimes used as a depth cue in paintings. Atmospheric physicists call it "air light." It is explained as light primarily from the sun and sky that is scattered by molecules and (especially) particles that are in the optical path between an observer and a target. Wooten and Hammond (2) originally argued that macular pigment, by absorbing this veiling haze, would improve the clarity of distant objects and increase visual range.

a batter with faster temporal vision would be able to "take more snapshots" of the pitch as it approaches home plate. Faster temporal processing speed would facilitate faster reaction times, thus enabling quicker decisions (eg, whether or not to swing at the pitch). Batters have a very short time (eg, 100 ms) to decide on a 95-mile-per-hour fastball. Put another way, someone with a relatively fast visual system would be able to gather as much information from a fast pitch (eg, amount of break on a curveball, the approximate speed of the pitch) as someone with slower temporal processing would be able to gather from a slower pitch (24).

EFFECTS OF LUTEIN AND ZEAXANTHIN ON GLARE DISABILITY, DISCOMFORT, CONTRAST, VISIBILITY, AND TEMPORAL PROCESSING SPEED

Sports performance is ultimately influenced by genetic, behavioral, cultural, socioeconomic, and environmental factors. Of these, dietary intake is certainly one of the most immediately modifiable. Yet, traditionally, the role of nutrients in sports has focused on deficiency issues (energy intake necessary to offset increased caloric expenditure, adequate hydration, general health, etc). The idea that nutrition could actually enhance performance is relatively new; the existing data have not been translated from the larger scientific literature on diet and visual performance in normal, healthy individuals to visual performance in baseball players.

One dietary factor that has been shown empirically to improve chromatic contrast, glare disability and discomfort, photostress recovery, visibility, and temporal processing speeds are the carotenoids lutein and zeaxanthin (2–4, 6–8). Carotenoids are a class of pigments (carotenes and xanthophylls) found primarily in green leafy vegetables and colored fruit. Approximately 750 carotenoids are found in nature, but only ∼24 have been identified within the different tissues of the body (25). In the body, the carotenoids tend to be accumulated with great specificity. For example, lycopene (abundant in tomatoes) is concentrated in the prostate, β-carotene (found, eg, in sweet potatoes and carrots) is concentrated in the corpus luteum, and lutein and zeaxanthin (found, eg, in kale and spinach) are concentrated in the eye and central nervous tissue (eg, occipital and frontal lobe; 10). In the brain lutein and zeaxanthin are thought to improve neural efficiency and processing speeds (8, 26).

Although these pigments are found in many tissues throughout the nervous system, where these carotenoids reach their highest concentration by far is in the macula (following a distribution that roughly parallels the cones; 14), and lutein and zeaxanthin at this site are termed the *macular pigments*. Their high density within the inner layers of the fovea (27) produces significant filtration of the short-wave light that would otherwise be incident on the cones (as high as 1.6 optical density units at 460 nm; 13). The highest concentration of lutein and zeaxanthin, indeed the highest concentration of carotenoids in the body, is therefore found in an area of the retina extremely vital to our ability to see.

It is probable that we evolved to accumulate these pigments in this important region because of their immediate effects on visual function (rather than long-term health effects they may also serve). There are at least 2 major immediate functions that are often proposed for the MPs and that have great relevance to baseball players: improving visual performance through optical means and increasing the speed by which visual information is processed.

LUTEIN AND ZEAXANTHIN AS OPTICAL FILTERS

Lutein and zeaxanthin are concentrated in the inner bilayers, and as such, they screen light before it is incident on the photoreceptors. The evidence to date suggests that these internal filters could reduce glare disability and discomfort, speed photostress recovery, and improve visibility through contrast enhancement.

As noted earlier, baseball players are likely often exposed to lighting conditions (eg, sunlight) that would induce visual deficits due to glare disability and discomfort). Stringham et al (3) showed that thresholds for glare discomfort (ie, photophobia responses, such as squinting of the eyes in reaction to an intense light) were much lower for light of short wavelengths (those in the blue region of the visible spectrum) compared with light of middle (green) or long (red) wavelengths. In other words, it took much less light energy to elicit an aversive response when the light was of a short wavelength. This effect is exaggerated in subjects with low retinal concentrations of lutein and zeaxanthin. Subjects with high concentrations experience much less visual discomfort when exposed to light with a significant short-wave component (such as the white light of the sun). In addition to causing discomfort (*see* also reference 6), bright light entering the eye (especially from a peripheral angle) will scatter and cause an individual to lose sight of an object in their line of sight (glare disability). Stringham and Hammond (4) showed that there is a strong relation between MP density and glare disability. In fact, individual variation in MP density explained 58% of the variance in grating visibility when using a broadband glare source (eg, achromatic xenon-white light). Supplementing 10 mg lutein and 2 mg zeaxanthin for 6 mo (5) led to direct improvements in glare disability that was proportional to increases in MP density. A similar effect was found for photostress recovery (sometimes called flash blindness). Bright light will bleach (isomerize) visual photopigment; MP filters light, which prevents the breakdown of photopigment. Because less photopigment needs to be regenerated, visual recovery is hastened as a direct function of MP amount (5, 6, 28).

In addition to blur and scatter arising from within the eye, visual degradation also occurs due to external optical sources. It may not be a coincidence that the peak absorbance of MP is 460 nm, which is also the peak wavelength of skylight. Wooten and Hammond (2) originally proposed that this preponderance of short-wave light in the atmosphere results in a bluish veiling luminance that degrades visibility—ie, how well and how far we can see targets outdoors. MP may improve vision through the atmosphere by preferentially absorbing the short-wave energy produced by blue haze, thereby increasing both the contrast within the objects that we view and the contrast of those objects with respect to their backgrounds. Extensive modeling by Wooten and Hammond (2) suggests that this effect could be very meaningful (empirical data are consistent with these predictions; 29, 30). For example, when viewing a series of parallel ridges covered with vegetation, ridges nearby will appear green. With each successive ridge, however, air light (for a review, *see* reference 30) reduces contrast, until distant ridges are lost in a milky bluish haze, even on a clear day (eg, Green River Area, WY; average visual range in June = 108 miles). The visibility hypothesis predicts that an individual with high MP would be able to distinguish such ridges up to 27 miles farther than individuals with little or no MP but equal Snellen acuity. A baseball player with high MP would see a broadband target such as a baseball sooner than a player with low MP (based on Wooten and Hammond's analysis, an ∼30% increase in visible range).

Another way that lutein and zeaxanthin might improve visual performance is by enhancing contrast. This effect is shown in **Figure 4**. A recent analysis of natural images (31) suggests that chromatic edges (ie, isoluminant) are relatively common. Luminance differences are often minimized when viewing images at a distance. In such cases, chromatic differences across the border often define the existence of an edge. It follows that colored filters that favor absorption of one side more than the other would enhance detection of an edge. As early as 1915, Luckiesh (32) reviewed the idea that yellow filters would improve visual performance by enhancing contrast. Luria (33) later demonstrated this effect by showing that the threshold for a yellow target on a blue background is reduced when viewed through a yellow (blue-absorbing) filter [Wolffsohn et al (34) confirmed this effect by using contrast measures]. Such effects are predictable based on the simple optics of colored filters. Reducing the luminance of a background relative to a target (or vice versa) increases contrast and therefore visibility. This simple optical effect likely has broad ecologic significance, because lutein and zeaxanthin act as blue-light filters. Wooten and Hammond (2) noted the fact that the preponderance of Rayleigh-scattered light (seen in blue haze and skylight, which peaks at ∼460 nm) creates a situation in which many targets are essentially viewed on short-wave (blue) backgrounds. Renzi and Hammond (7) recently showed that contrast enhancement was linearly related to individual differences in MP when viewing chromatic borders: the more the chromatic differences favored differential absorption by the macular pigments, the greater the enhancement or detectability of an edge. As noted by Mollon and Regen (35), "to the list of possible functions of the macular pigment, we could add the enhancement of chromatic contrast in the arboreal theater in which primates emerged."

There is a large body of literature suggesting that tinted contact lenses can improve a range of visual abilities including better contrast discrimination in bright sunlight and reduced photostress recovery times (36–38). Similarly, tinted intraocular lenses (eg,

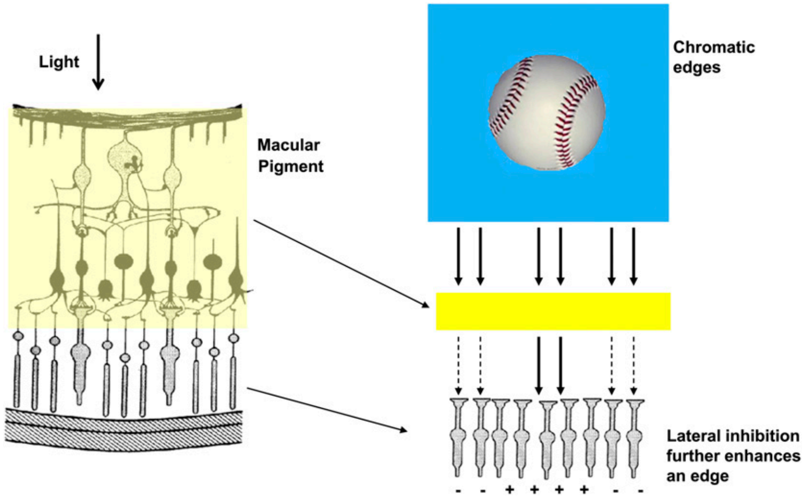

FIGURE 4. The influence of a yellow filter on enhancement of chromatic edges such as those encountered by baseball players when viewing a ball against the blue sky.

Acrysof natural; Alcon) have been shown to reduce photostress recovery times, reduce glare disability, and improve contrast discrimination (39, 40). As originally noted by Wooten and Hammond (2), however, none of these studies used lenses that were designed to match the spectral absorbance characteristics of lutein and zeaxanthin, the yellow chromophores that are naturally found within the visual system. Moreover, no studies to date have actually measured the concentrations of lutein and zeaxanthin within the retina itself (additional filtration could be superfluous for individuals with high MP concentrations). As early as 1933, Walls and Judd (41) argued that one reason that so many species evolved to use colored intraocular filters (specifically yellow and often carotenoids) was to improve visual function, namely, glare disability, visibility by blue haze reduction, and contrast enhancement. As opposed to using external colored lenses or yellow intraocular filters, increasing natural concentrations of lutein and zeaxanthin within the visual system can produce significant optical improvements without the consequence of added filtration reducing luminance. This is because the visual system can compensate for light loss due to MP filtering (28, 42) by increasing neural gain. Hence, vision, even under poor lighting conditions, is not adversely affected (indeed, lutein and zeaxanthin supplementation actually improves mesopic acuity; 43).

LUTEIN AND ZEAXANTHIN AND NEURAL EFFICIENCY

In addition to high concentrations in the eye, lutein and zeaxanthin make up ∼66–77% of the total carotenoid concentration in both the frontal lobe and in the visual processing regions of the brain, such as the striate cortex and visual association cortices (10, 44); in fact, concentrations within the retina are highly correlated to concentrations within the brain, especially cerebellum (44) (a region highly involved in muscular coordination and equilibrium). Consequently, lutein and zeaxanthin are optimally positioned in regions of the central nervous system that are critical for visual (motor and cognitive) processing. Lutein and zeaxanthin are long-chain molecules that are incorporated within lipid-rich cell membranes (45) and axonal projections (46). Within the neural membrane, lutein is positioned both orthogonal to, and flush with, the lipid bilayer (45). In its orthogonal configuration, lutein serves as structural support for a membrane that is PUFA-rich and fluidic. In its parallel state, lutein influences the formation of gap junctions and second messenger systems, which enhance interneuronal and neural-glial communication (47, 48). This type of in vitro evidence, combined with the observation that the pigments are present in brain tissue, suggests the pigments could influence the actual processing of visual information. There is some evidence for this idea. A recent study by Johnson et al (49) for example, found that the MP carotenoids were related to measures of cognitive function such as verbal fluency, memory, processing speed, and accuracy. MP has also been found to be significantly related to temporal processing speeds using visual stimuli (8, 26). More recently, Dengler et al (50) tested younger (aged 18–30 y) and older [mean age: 74 y (approximately half with mild cognitive impairment to assess the role of lutein and zeaxanthin in cognition)] subjects to assess the relation between lutein and zeaxanthin (measured in the retina but assumed to also reflect concentrations in the brain) and visuomotor function. Visuomotor function was measured by using balance time and coincidence anticipation timing: subjects tracked a light moving at varying speeds along a linear track and tried to anticipate arrival at a target location. MP optical density was significantly ($P < 0.05$) related to reaction time and to balance ability in the older subjects. Even in the younger group, MP optical density was significantly ($P < 0.05$) related to fixed and variable position reaction time as well as to the number of errors committed on the coincidence anticipation task at high speed. The cognitive function of the 52 elderly participants was also measured with the Repeatable Battery for the Assessment of Neuropsychological Status. In this trial, MP optical density was related to visuospatial cognition in all participants ($P = 0.03$), with the relation between MP optical density and visuospatial cognition stronger in impaired participants ($P = 0.02$). In this wide sampling of different-aged subjects, visuomotor ability was universally improved.

If lutein and zeaxanthin do have direct facilitative effects on neural function, this would likely be an advantage to baseball players. A pitch thrown at about 80 miles per hour reaches a batter in ∼0.5 s. As shown by Renzi and Hammond (8), going from low to high MP is related to temporal vision that is improved by

~3 Hz (3 cycles/s). When measuring the entire temporal modulation transfer function, this improvement was ~15%. Essentially, such faster vision would allow one to "take more snapshots" of a pitch as it approaches home plate. This would facilitate faster reaction times, thus enabling quicker decisions (eg, whether or not to swing at the pitch). Even minor improvements in visual processing speed would be absolutely crucial to batters because they have a very short time (eg, 100 ms) to decide on a 95-mile-per-hour fastball.

It is likely that effects on visual speed and motor function are useful to both athletes and nonathletes alike.

CONCLUSIONS

Abernethy (51) originally conceptualized efforts to improve the visual performance of athletes as a hardware versus software problem, where hardware represents the physical characteristics of a player's visual system and software is the cognitive strategies and perceptual challenges inherent to a given sport. This review raised the possibility that both hardware and software might be improved through focused nutritional interventions. For example, supplementation with lutein and zeaxanthin could potentially improve visual performance by increasing both the hardware (optical effects within the eye) and software (cognitive and processing abilities) capabilities of the system. Such visual improvements are likely most important for individuals with diets that are deficient (eg, war veterans with poor diets; 52). Busy schedules, high caloric/energy needs, etc, all likely contribute to a relatively poor diet for many athletes (1, 12). Low retinal concentrations of lutein and zeaxanthin are likely particularly significant for baseball players because they are also exposed to high levels of actinic light [recent empirical data from Barker et al (53) have shown direct effects of lutein and zeaxanthin in protecting the retina from actinic light stress]. There is now a very large body of evidence supporting the role of lutein and zeaxanthin in the protection of the retina and crystalline lens from blue-light–induced photooxidative damage [*see* the review by Schalch et al (54)]. Hence, the recommendation that players would benefit from increased MP is not just for the goal of improving visual performance but also as a means of providing increased protection for a group that is particularly vulnerable. The technology for measuring MP directly and in vivo is now widely available (55). Future studies should take advantage of such methods to study the lutein and zeaxanthin status of athletes directly.

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