Visual Acuity and Contrast Sensitivity Testing for Sports Vision

Article *in* Eye & contact lens · March 2011

DOI: 10.1097/ICL.0b013e31820d12f4 · Source: PubMed

Visual Acuity and Contrast Sensitivity Testing for Sports Vision

Aaron B. Zimmerman, O.D., M.S., *Kimberly L. Lust,* B.S., *and Mark A. Bullimore,* M.C.Optom., Ph.D.

Abstract: The building blocks of effective sports vision are visual acuity and contrast sensitivity. Proper measurement of these spatial vision attributes is necessary for repeatability in the clinic or in the laboratory. The most repeatable method of testing visual acuity is with logMAR charts—either the Bailey–Lovie chart or the Early Treatment Diabetic Retinopathy Study chart. The Pelli–Robson and the Mars are the most repeatable contrast sensitivity tests. Athletes may or may not demonstrate superior visual acuity and contrast sensitivity compared with age-matched nonathlete populations, and the optical quality of their eyes may be similar. Dynamic visual acuity in athletes and their performance are typically superior to those of nonathletes. How these differences relate to on-field performance is not known. Other changes to the visual system because of refractive surgery or contact lens wear may increase higher order aberrations and reduce low-contrast visual acuity. The ability to improve already-normal visual acuity is unclear although contrast sensitivity can improve with fast-paced video games. Tinted contact lenses help reduce discomfort glare and speed up adaptation but do not have an appreciable effect on visual acuity and contrast sensitivity.
Conclusion: The use of valid and repeatable visual acuity and contrast sensitivity tests is essential for measuring the differences in visual performance among athletes and nonathletes. The development of a standardized dynamic visual acuity test is needed as are well-controlled scientific studies to evaluate the benefits of sports vision training

Key Words: Visual acuity—Contrast sensitivity—Vision of athletes—Vision training—Dynamic visual acuity.

(*Eye & Contact Lens* 2011;37: 153–159)

The ''Sports Vision 2010—A New Paradigm'' meeting took place in early 2010 with multiple professions being represented, including ophthalmology, optometry, and athletic trainers. A theme of the meeting was the *Vision Pyramid* (Fig. 1) consisting of various visual system characteristics and their integration to achieve the ultimate goal of on-field performance enhancement. At the base of the pyramid lies visual acuity and contrast sensitivity, which are the fundamentals of visual performance. This article will discuss the science of visual acuity and the contrast sensitivity function (CSF), their limitations, how to properly test these variables, the effect of refractive correction, and whether or not training is beneficial. Furthermore, the potential for the inclusion of dynamic presentation of test targets—whether briefly presented or moving—is discussed along with the potential for enhancement using tinted lenses and vision training.

Visual acuity and contrast sensitivity are two aspects of spatial vision assessed in clinical and research settings. Visual acuity is a measure of an individual's ability to resolve fine detail, that is, what is the smallest black-on-white letter that a subject can identify. Contrast sensitivity is the individual's ability to detect low-contrast objects of various sizes. In the laboratory, contrast sensitivity—the reciprocal of threshold contrast—is measured for sine wave gratings for a range of spatial frequencies, specified in cycles/degree. Low spatial frequencies correspond to broad stripes, whereas high spatial frequencies correspond to narrow stripes. The CSF has an inverted U shape with the peak contrast sensitivity at approximately 4 cycles/degree meaning that the human visual system is relatively less sensitive to high and low spatial frequencies (Fig. 2).[1] The highest spatial frequency that can be detected at 100% contrast corresponds to the subject's visual acuity. Thus, contrast sensitivity and visual acuity are related, although the former is a more complete description of visual performance.

An individual's visual acuity is physiologically limited optically, retinally, and cortically. The optical limitations of the eye are because of pupil size and aberrations induced by the cornea and the lens. The normal pupil size for young adults is typically approximately 5.3 mm, whereas that of a 60-year-old is 3.2 mm.[2] A larger pupil can make the aberrations of the eye manifest, whereas a smaller pupil can degrade the image through diffraction. Spherical aberration is present in normal eyes and increases as the pupil dilates.[3]

Orthokeratology is a specialty contact lens fit utilized to reversibly reduce a patient's myopia. Cone density at the center of the fovea is approximately 200,000 cones/mm^2 with cone spacing being 2.5 μm. Each photoreceptor subtends approximately 28 arcsec, and this allows for just a little greater than 60 cycles/degree or slightly better than 20/10 Snellen visual acuity.[4] This limitation is commonly referred to as the Nyquist limit.[5] Recent advancements with adaptive optics, particularly scanning laser ophthalmoscopy, have confirmed that the photoreceptor density in vivo correlates well with the Curcio et al. data from harvested retinas.[4,6,7] The visual pathway advances to the ganglion cells, then the lateral geniculate nucleus, and ends at the visual cortex. The upstream structures do not currently have any known properties capable of enhancing the spatial visual acuity.

logMAR Visual Acuity Charts

There are numerous methods used to test visual acuity. The most common method used is recognition acuity or resolving an optotype in which the patient is familiar with the target. The most repeatable and standardized method of measuring visual acuity is through the

From the College of Optometry, The Ohio State University, Columbus, OH.

The authors have no funding or conflicts of interest to disclose.

Address correspondence and reprint requests to Aaron B. Zimmerman O.D., M.S., College of Optometry, The Ohio State University, 338 West 10th Avenue, Columbus, OH 43210; e-mail: azimmerman@optometry.osu.edu

Accepted December 23, 2010.

DOI: 10.1097/ICL.0b013e31820d12f4

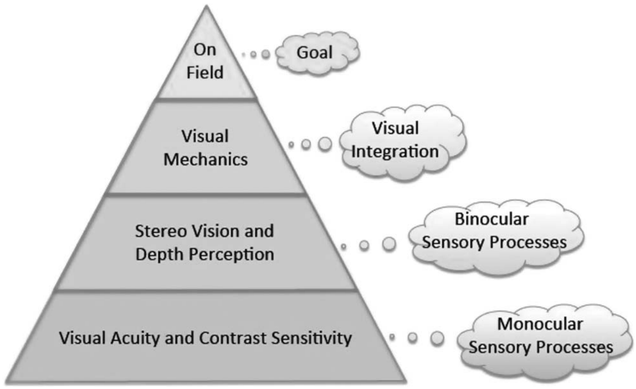

FIG. 1. The vision pyramid. Reprinted with permission from Kirschen DG, Laby DM. The role of sports vision in eye care today. *Eye Contact Lens* 2011;37;127-130. Copyright 2011 Contact Lens Association of Ophthalmologists, Inc.

use of logMAR charts. Two types of logMAR are commonly used: the Bailey–Lovie chart[8] and the Early Treatment Diabetic Retinopathy Study (ETDRS) chart,[9] and these have become standard in all federally funded clinical studies and many under the auspices of the United States Food and Drug Administration. Both charts use 10 letters chosen to have similar legibility. The Bailey–Lovie chart uses the letters D, E, F, H, N, P, R U, V, Z, which are 5:4 height to width. The ETDRS chart uses Sloan letters C, D, H, K, N, O, R, S, V, Z, which are 5:5 in height to width.

Each line on the logMAR charts contains five letters of equal size, separated by equal distance. The spacing between lines is the same height as the preceding letter height, such as the spacing between the 20/25 and 20/32 lines is the height of the 20/25 line. The chart also consists of a uniform line size reduction of 1.25 or 0.1 log units. Because five letters are on each line, each individual letter is assigned a value of 0.02. Instead of giving credit for an entire line, this test allows for visual acuity to be measured and specified on a letter-by-letter basis. This both improves the repeatability of the measurement and allows more precise specification of visual acuity.[10] Clinicians often give patients credit for a partial line read, and the by-letter scoring approach formalizes this notion. Visual acuity testing can be made more rigorous by forcing the patients to guess letters even if they say they cannot read them.

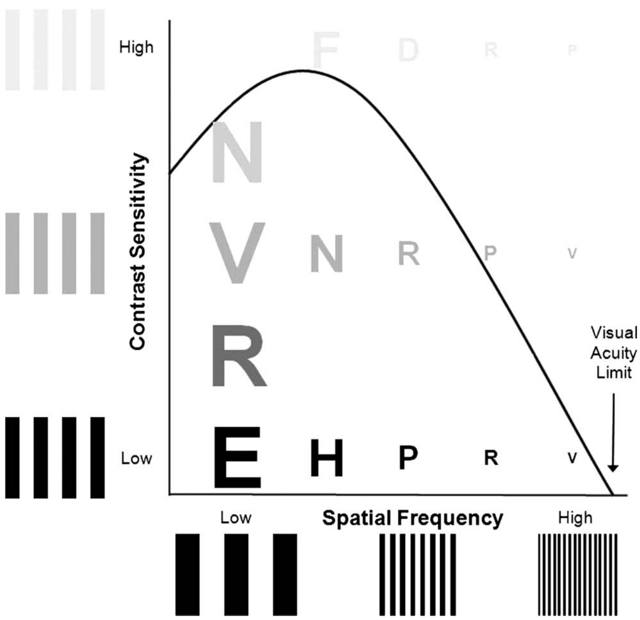

FIG. 2. The contrast sensitivity function.

Contrast Sensitivity Charts

Several researchers have advocated the use of letters to assess contrast sensitivity. Letters have the advantage of being familiar to patients, and their forced-choice properties means that the patients do not merely have to state whether or not they can see a grating or choose between a limited number of orientations with a relatively high chance of guessing correctly. Pelli et al.[11] were among the first to assert that the CSF could be adequately described by two points on the function: visual acuity corresponding to the high spatial cut-off and contrast sensitivity for large letters corresponding to the height of the CSF (Fig. 2).To facilitate rapid assessment, Pelli et al. introduced the Pelli–Robson Chart, which consists of 5-cm-high letters of decreasing contrast. The Pelli–Robson chart has 16 triplets of Sloan letters with decreasing contrast. Each triplet is 0.15 log units lower in contrast than its predecessor, and repeatability can be further improved by assigning each letter a value of 0.05 log units.[12] Each letter subtends 2.8° at a test distance of 1 m.

Elliott and Bulllimore[13] demonstrated that contrast sensitivity could be measured with greater repeatability with letter-based charts, including the Pelli–Robson Chart, than with charts containing gratings. In the 20 years since the introduction of the Pelli–Robson Chart, a few similar tests have been introduced. The Mars Letter Contrast Sensitivity Test is a smaller more portable derivative of the Pelli–Robson chart.[14] These charts are 23 × 35.5 cm, whereas the Pelli–Robson chart is 63 × 86 cm. The Mars test consists of eight rows of six letters, but each letter is lower in contrast by 0.04 log units than the previous. Dougherty et al.[15] found that the Pelli–Robson and Mars charts demonstrated similar repeatability and showed good agreement. The Mars test may be more practical in the sports vision setting because it is much more portable and durable.

Dynamic Visual Acuity Tests

Many sports challenge the participant to localize and track a fast moving object such as a baseball, a tennis ball, or a hockey puck. This raises the question of whether vision tests that incorporate moving targets could be developed and used . Currently, there is no widely accepted or standardized method to assess dynamic visual acuity. Dynamic visual acuity has been tested with targets moving laterally on a screen, on a rotating disc, or using projected letters imaged by rotating mirrors, with either letters or numbers as stimuli. For the laterally moving targets variations in stimulus duration, luminance, target size, contrast, and eccentricity have all been tested.[16–19] It is well established that as the target velocity increases, an individual's visual acuity will decrease.[16,18,19] It is also clear that stimulus duration has an effect on dynamic visual acuity.[18] It has also been shown that dynamic visual acuity can be improved with training.[17]

Clinicians have been interested in studying dynamic visual acuity hypothesizing that it is related to athletic performance. According to Rouse et al.,[20] it would be more advantageous for an athlete to discriminate rather than just detect a target, for example, the laces on a baseball. Ludvigh and Miller performed many studies regarding aviation, and their study indicates that pilots with better dynamic visual acuity make fewer errors. Rouse et al.[20] compared the dynamic visual acuity of members of the California State University at Fullerton baseball team with that of optometry students from the Southern California College of Optometry. The subjects had to identify the orientation 20/25 Landolt Cs projected for 400 msec at varying velocities. They found that the baseball players could, on average, identify the orientation at significantly higher velocities.

Other researchers have used briefly presented targets to evaluate vision. This is particularly useful when assessing a patient whose vision may be fluctuating because of variations in tear film or movement of a contact lens.[21,22] Indeed differences in performance can be identified that are not apparent for static targets. Other researchers have made objective dynamic evaluations of ocular image quality using aberrometry and demonstrated the importance of the tear film.[23,24]

The final class of dynamic vision tests is kinetic visual acuity where the target is moved toward the subject.[25] This approach is analogous to gradually or rapidly increasing the size of a letter until a subject can identify it, and thus, results will be influenced by both visual acuity and reaction time.

In summary, the assessment of vision for dynamic, moving targets seems to be a potentially fruitful avenue of investigation and development. Many test variables can be manipulated including letter size, target velocity, contrast, and exposure duration, and the challenge is to standardize these into a repeatable, valid test that can then be used to discriminate among groups of subjects or to assess the benefits of a vision-training regimen. Incorporating the principles of existing static clinical tests such as logMAR charts or using Landolt Cs would seem desirable. For example, Bailey–Lovie or ETDRS charts use letters of relatively equal resolution difficulty and follow a uniform (logarithmic) size progression.[8,9] It would also be possible to develop a low contrast or a variable contrast chart.

How Does Athletes' Vision Compare With That of the Normal Population?

The largest study to date evaluating the performance of the visual system in athletes was performed by Laby et al.[26] in the 1990s. During Baseball spring training from 1992 to 1995, these investigators performed thorough vision screeners evaluating static visual acuity, contrast sensitivity, and distance and near stereoacuity (including random dot) on players from the Los Angeles Dodgers.

Nearly 80% of the Major League Baseball (MLB) players were found to demonstrate static visual acuity of 20/15 (−0.125 logMAR) or better. Only 1.3% of the players showed visual acuity of 20/30 (+0.20 logMAR) or worse (Fig. 3). Some players even approached 20/9 (−0.35 logMAR). These values are impressive when compared with our historical benchmark of 20/20, but most young *normal* subjects demonstrate visual acuity that is better than 20/20. The oft-cited work of Elliott et al.[27] reports a mean visual acuity of –0.13 logMAR in 18- to 24-year-olds and –0.16 logMAR in 25- to 29-year-olds. Inspection of their data (Fig. 4) suggests that approximately 60% of their subjects between 20 and 35 years old demonstrate visual acuity of 20/15 or better and approximately 20% demonstrate 20/12.5 or better. In other words, the visual acuity of the Laby et al. baseball players may be superior to those of a normal population, but only by a letter or two.

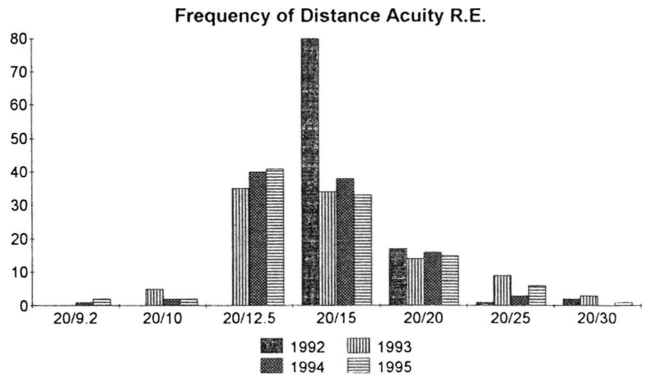

FIG. 3. The distribution of visual acuity among Major League Baseball players. Reprinted with permission from Laby DM, Rosenbaum AL, Kirschen DG, et al. The visual function of professional baseball players. *Am J Ophthalmol* 1996;122:476–485.

Laby et al. also measured contrast sensitivity in their cohort of baseball players and found superior values when compared with unpublished normal values at higher spatial frequencies. On some of the tests, the players could identify the lowest contrast stimuli, but given the design of the tests, the probability of guessing correctly is high. Hoffman et al.[28] found higher contrast sensitivity in college baseball players compared with in an optometry student control group using the Arden Plates. Unfortunately, this test is criteria dependent (''tell me when you see it'') and may be further confounded by the reaction times of the subjects. Although contrast sensitivity may be higher among elite athletes, these previous reports are worthy of further investigation using a concurrent control group and well-designed tests.

One potential explanation for higher visual performance among athletes is lower ocular aberrations. To this end, Kirschen et al.

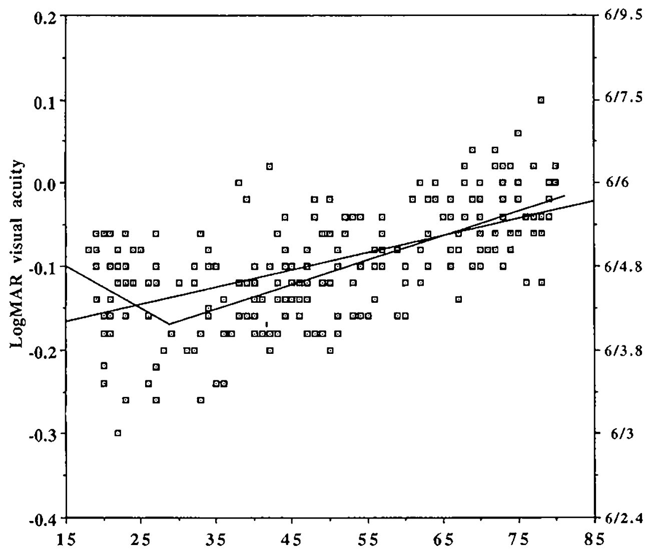

FIG. 4. The distribution of visual acuity among eyes of 223 normal healthy subjects ranging from 18 to 80 years of age. The best linear and bilinear fits are shown. Reprinted with permission from Reprinted with permission from Elliott DB, Yang KC, Whitaker D. Visual acuity changes throughout adulthood in normal, healthy eyes: Seeing beyond 6/6. *Optom Vis Sci* 1995;72:186–191.

assessed higher order aberrations in professional baseball players and compared them with published controls.[29,30] The only significant difference between these two populations was for trefoil, but the 0.0147-μm difference corresponds to a 0.031-D equivalent spherical difference for a 4-mm pupil and was thus judged to be clinically irrelevant. This finding is consistent with that of Villegas et al.[3] who found that lower levels of ocular aberrations did not explain the supernormal visual acuity observed in some subjects.

In summary, high levels of visual performance may exist among elite athletes, but future research should recruit concurrent control groups and test them under identical conditions using appropriately designed methodology. Differences in performance are unlikely to be because of ocular aberrations, and thus, their correction in a normal population may not lead to measurable improvements in vision.

Refractive Modification

According to the International Society of Refractive Surgery U.S. 2009 Trend Survey, laser in situ keratomileusis (LASIK) continues to be the most common form of refractive surgery, and many high-profile athletes have undergone the procedure.[31,32] It is unclear whether LASIK results in an improvement or detriment of on-field performance, for example, in baseball players.[33] It is has been shown that best-corrected high contrast visual acuity is unaffected by LASIK; however, low-contrast visual acuity is reduced for individuals with greater than −6 D of preoperative myopia and those who have undergone LASIK with astigmatic keratectomy.[34] Marcos et al.[35] found that higher order aberrations increased significantly after LASIK, with higher preoperative levels of myopia demonstrating a larger increase in aberrations. A recent study has shown that with wavefront-guided LASIK spherical aberration does not change significantly for myopia up to −7 D.[36]

Orthokeratology has been used since 1989 to reversibly reduce a patient's myopia. Similarly to LASIK flattening, the central corneal surface leads to more spherical aberration and reduced low-contrast visual acuity.[37] In both of these refractive procedures, the practitioner and patient should be aware of the potential reductions in visual performance, particularly under nighttime conditions when the pupil will be larger. For individuals pursuing LASIK surgery, the amount of refractive error being corrected needs to be considered, and wavefront-guided procedures are preferred. Orthokeratology is reversible with discontinuation of lens wear and thus may be considered in younger athletes.

There are some circumstances where refractive error has little effect on sports performance. Applegate and Applegate[38] studied the effects of induced refractive error on free throw shooting. Grade school and high-school basketball players were blurred using trial lenses and shot 25 free throws for each condition. Figure 5 shows that the percentage of free throws made goes down immediately if the subject is blurred to 20/40. This decrease in shooting percentage was not statistically significant, although a 10% improvement in free throw shooting over an entire season may be meaningful. As blur was increased, the shooting percentage stayed nearly identical. Thus, uncorrected refractive error for a static, repeatable motion such as free throw shooting may not be critical.

Mann et al.[39,40] have recently evaluated the impact of blur on the more visually demanding and high velocity game of cricket. Male batsmen were instructed to hit cricket balls that were projected toward them by either a bowling (pitching) machine or a live bowler at two different velocities, medium and fast. Each batsman was blurred using soft contact lenses allowing for four conditions: plano, +1.00, +2.00, and +3.00 D with the players' habitual correction used for the plano condition. These conditions yielded visual acuities of approximately 20/15, 20/40, 20/60, and 20/160. Although, one would suspect that blur would have a significant effect on hitting performance, their results suggest that there is no decrease in performance until the +3.00-D condition (Fig. 6).[40] This effect was found not only with a predictable and repeatable pitching machine but also with nonpredictable human bowlers (pitchers).

Blur may not cause a significant reduction in athletic performance in a sport with fast moving targets, because of the dorsal vision pathway. Because the magnocellular pathway has

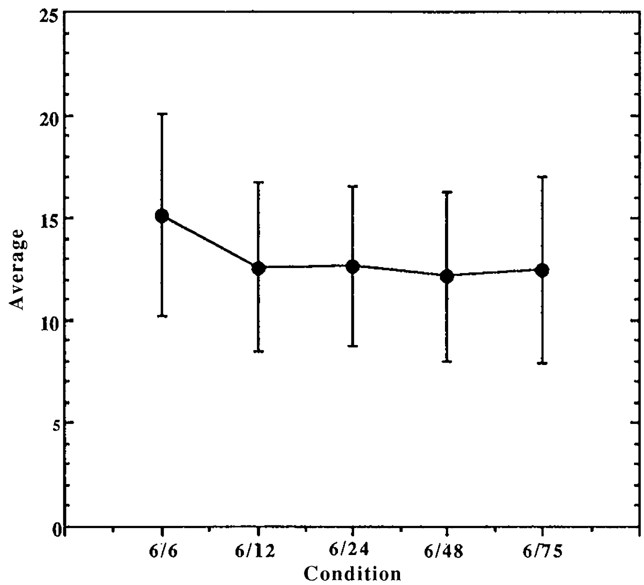

FIG. 5. The relation between basketball free throw shooting and visual acuity. Reprinted with permission from Applegate RA, Applegate RA. Set shot shooting performance and visual acuity in basketball. *Optom Vis Sci* 1992;69:765–768.

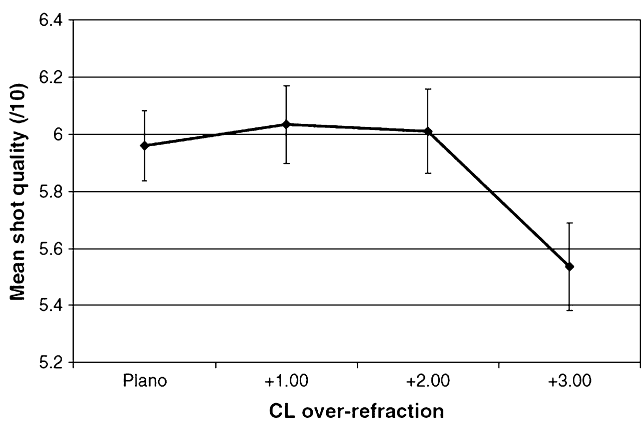

FIG. 6. The effect of blur on cricket shot quality. Reprinted with permission from Mann DL, Ho NY, De Souza NJ, et al. Is optimal vision required for the successful execution of an interceptive task? *Hum Mov Sci* 2007;26:343–356.

large receptive fields and is relatively insensitive to high spatial frequencies, it can be surmised that low levels of blur will not dramatically decrease performance.

Training Visual Acuity

It is well established that vision training including occlusion and other forms of penalization is an effective treatment for amblyopia, particularly in the younger patient.[41] More controversial is the use of vision therapy to improve uncorrected visual acuity in myopia. Multiple techniques have been attempted with some claiming reduction in the degree of myopia.[42,43] Trachtman's and Randle's work, although independent, used devices to measure accommodative accuracy, which fed into a tone generator to give feedback to the subject regarding their accommodative status. Trachtman's goal was to treat functional myopia, which was defined as less than 2 D of myopia. He found that he could treat between 0.25 and 0.75 D of myopia. Randle's studies demonstrated that subjects could voluntarily control their accommodative systems and subjects could extend their far point. Unfortunately, neither researcher evaluated pre and postcycloplegic refraction to determine whether refractive status truly changed. Balliet et al.[44] tried to train visual acuity by having subjects view oblique square wave gratings whose optical distance was varied. Improvements in visual acuity were found and attributed to changes in the tear lens, although refractive status was unchanged.

Gilmartin[45] summarized myopia-reduction therapy in a 1991 review article and concluded that there is no experimental evidence to indicate that training visual acuity through biofeedback is effective. He was careful not to dismiss the theory of biofeedback treating myopia but emphasized the need for objective data. The American Academy of Ophthalmology dismisses any current treatment for reducing myopia and believes that the only risk associated with this therapy is financial.[46] http://www.eyecareamerica.org/eyecare/treatment/alternative-therapies/visual-training.cfm.

Contrast Sensitivity Enhancement

Devices

Tinted spectacle lenses have long been used in some sports including shooting and archery. Subjective improvements in vision are common although not accompanied by objective improvements in contrast sensitivity.[47] The Nike Maxsight contact lenses (Bausch + Lomb, Rochester, NY) were introduced in 2005 and were designed to improve on-field performance. These lenses have since been discontinued; however, studies have been published regarding the effect these lenses had on visual performance.

Early reports suggested no improvements in visual acuity or contrast sensitivity with Nike Maxsight contact lenses.[48] Subsequently, Porisch[49] compared contrast sensitivity with Nike Maxsight contact lenses and with clear lenses of collegiate and professional athletes by comparing performance either. A significant difference was found only at 3 and 18 cycles/degree, corresponding to 1 to 2 letters on the Pelli–Robson chart. Subjects also reported a decrease in glare. This is consistent with subjective responses from the Erickson et al.[50] study in which visual performance and comfort of clear and tinted lenses were compared in bright lighting conditions. Erickson et al. found that dark-adapted subjects were able to visually adapt faster to bright light conditions with the tinted lenses, and they also found that subjects noticed significantly less glare with tinted lenses as compared with clear lenses.

Yellow-tinted contact lenses block out shorter wavelength light, particularly blue light. Benefits may thus accrue because of reduction in the longitudinal chromatic aberration of the eye or reduction in intraocular light scatter. Although the effect of yellow-tinted lenses on visual acuity and contrast sensitivity is equivocal, there may still be a role based on subjective preference, and specific tints for specific sports may be appropriate. Former MLB player Mark McGwire used yellow tinted lenses toward the end of his career and claimed that these lenses allowed for crisper vision and a reduction in glare.[51]

Therapy

Recent studies have suggested that contrast sensitivity may be enhanced in normally sighted subjects.[52] The investigators compared contrast sensitivity of individuals who commonly play video games and nonvideo game players. The video game players showed higher contrast sensitivity at mid and high spatial frequencies. In a confirmatory experiment, a sample of nonvideo game players were assigned to two groups: one group played action video games (*Call of Duty 2* by Infinity Ward, Encino, CA), and the control group played a nonaction game (*The Sims 2 by* Electronic Arts, Redwood City, CA). Only those exposed to the action video game demonstrated a significant improvement in contrast sensitivity. The investigators suggest that because of cortical plasticity, contrast sensitivity can be improved.

New techniques may offer benefits in the area of sports vision. For example, recent reports suggest improvements in contrast sensitivity in older amblyopic subjects, a population that historically has not been offered therapy.[53] The investigators trained amblyopes, aged 9 to 55 years, using sine-wave patches, with and without flanking high-contrast patches.[54] The investigators found that by reconstructing those elements that were not acquired during development, visual acuity and contrast detection could be improved. Because 100% contrast stimuli are rare in the natural world, showing good contrast sensitivity may be more important than superior visual acuity for overall visual performance. Superior contrast sensitivity comes from demonstrating healthy and optimally corrected eyes; however, new studies are showing that the visual components responsible for perceiving contrast may have plasticity. The question of whether training contrast sensitivity helps improve on-field performance will need to be addressed.

Concluding Comments

To date, there have been limited controlled studies evaluating sports vision therapy. Wood and Abernethy[55] evaluated 30 subjects placed in three groups: a vision therapy group, a placebo, and a control group. The exercises used in the vision-training group were common vision therapy techniques used in clinical practice. Their results showed that the vision training did not have any effect. They later performed an additional study with four groups. The first group was administered a sports vision–specific battery of therapy, the second group was administered a different vision therapy regimen, the third group was a placebo, and the fourth was a control. Again, there was no difference with performance. Specifically, static visual acuity and dynamic visual acuity did not improve.

The most fundamental aspects of sports vision are contrast sensitivity and visual acuity. Visual acuity is tested on a daily basis, and in most circumstances, treating refractive error is the easiest way to quickly improve visual acuity. Contrast sensitivity is not necessarily a routine part of a vision examination, yet it has an important role in daily life and on the field of play. Appropriate testing of these tests is important for repeatable and reliable results. This is important because it has been suggested that athletes' visual performance is superior to that of nonathletes. Although this certainly may be true, the margins between these two groups are not substantial, so usage of a reliable test is essential.

It is possible that dynamic visual acuity may be the most important measure of an athlete's visual system. Most sports have rapidly moving objects and individuals, and it is essential that a player is capable of not only detecting targets but also able to discriminate subtle differences. All components of dynamic visual acuity, meaning velocity, presentation time, optotype orientation, and target size need to be addressed, and it is possible that each component may need to be tested individually. It is also essential that a well-accepted standardized dynamic visual acuity system be developed for valid comparisons to be made in the future.

Any athlete undergoing refractive modification by either refractive surgery or reverse geometry lenses needs to be informed of the possible reduced quality of vision at night. Vision training to reduce myopia has little scientific support,[45,56] but contrast sensitivity may be able to be improved with certain training tasks. It remains to be demonstrated whether more contrast sensitivity translates to sports performance.

The sports vision pyramid is a good model describing the hierarchy of the visual components necessary for superior sports vision. Training the higher levels of the pyramid is predicated on having the best possible corrected visual acuity and contrast sensitivity. Verifying that sport specific vision training improves and athletes' performance currently has anecdotal support but clearly needs scientific evidence. This may be challenging because of the number of variables associated with athletic competition but is not unobtainable.

REFERENCES

1. Campbell FW, Robson JG. Application of Fourier analysis to the visibility of gratings. *J Physiol* 1968;197:551–566.
2. Owsley C, Sekuler R, Siemsen D. Contrast sensitivity throughout adulthood. *Vision Res* 1983;23:689–699.
3. Villegas EA, Alcon E, Artal P. Optical quality of the eye in subjects with normal and excellent visual acuity. *Invest Ophthalmol Vis Sci* 2008;49:4688–4696.
4. Curcio CA, Sloan KR, Kalina RE, et al. Human photoreceptor topography. *J Comp Neurol* 1990;292:497–523.
5. Williams D. Seeing through the photoreceptor mosaic. *Trends Neurosci* 1986;9:193–198.
6. Roorda A. Applications of adaptive optics scanning laser ophthalmoscopy. *Optom Vis Sci* 2010;87:260–268.
7. Chui TY, Song H, Burns SA. Individual variations in human cone photoreceptor packing density: Variations with refractive error. *Invest Ophthalmol Vis Sci* 2008;49:4679–4687.
8. Bailey IL, Lovie JE. New design principles for visual acuity letter charts. *Am J Optom Physiol Opt* 1976;53:740–745.
9. Ferris FL III, Kassoff A, Bresnick GH, et al. New visual acuity charts for clinical research. *Am J Ophthalmol* 1982;94:91–96.
10. Bailey IL, Bullimore MA, Raasch TW, et al. Clinical grading and the effects of scaling. *Invest Ophthalmol Vis Sci* 1991;32:422–432.
11. Pelli DG, Robson JG, Wilkins AJ. The design of a new letter chart for measuring contrast sensitivity. *Clin Vision Sci* 1988;2:187–199.
12. Elliott DB, Bullimore MA, Bailey IL. Improving the reliability of the Pelli–Robson contrast sensitivity test. *Clin Vision Sci* 1991;6:471–475.
13. Elliott DB, Bullimore MA. Assessing the reliability, discriminative ability, and validity of disability glare tests. *Invest Ophthalmol Vis Sci* 1993;34:108–119.
14. Arditi A. Improving the design of the letter contrast sensitivity test. *Invest Ophthalmol Vis Sci* 2005;46:2225–2229.
15. Dougherty BE, Flom RE, Bullimore MA. An evaluation of the Mars Letter Contrast Sensitivity Test. *Optom Vis Sci* 2005;82:970–975.
16. Miller JW, Ludvigh E. The effect of relative motion on visual acuity. *Surv Ophthalmol* 1962;7:83–116.
17. Long GM, Rourke DA. Training effects on the resolution of moving targets–Dynamic visual acuity. *Hum Factors* 1989;31:443–451.
18. Long GM, May PA. Dynamic visual acuity and contrast sensitivity for static and flickered gratings in a college sample. *Optom Vis Sci* 1992;69:915–922.
19. Geer I, Robertson KM. Measurement of central and peripheral dynamic visual acuity thresholds during ocular pursuit of a moving target. *Optom Vis Sci* 1993;70:552–560.
20. Rouse MW, DeLand P, Christian R, et al. A comparison study of dynamic visual acuity between athletes and nonathletes. *J Am Optom Assoc* 1988;59:946–950.
21. Ridder WH III, Tomlinson A. The effect of artificial tears on visual performance in normal subjects wearing contact lenses. *Optom Vis Sci* 2003;80:826–831.
22. Thai LC, Tomlinson A, Ridder WH. Contact lens drying and visual performance: The vision cycle with contact lenses. *Optom Vis Sci* 2002;79:381–388.
23. Himebaugh NL, Thibos LN, Bradley A, et al. Predicting optical effects of tear film break up on retinal image quality using the Shack–Hartmann aberrometer and computational optical modeling. *Adv Exp Med Biol* 2002;506:1141–1147.
24. Tutt R, Bradley A, Begley C, et al. Optical and visual impact of tear break-up in human eyes. *Invest Ophthalmol Vis Sci* 2000;41:4117–4123.
25. Wu J, Lu S, Miyamoto S, Hayashi Y. New definitions of kinetic visual acuity and kinetic visual field and their aging effects. *IATSS Res* 2009;33:27–34.
26. Laby DM, Rosenbaum AL, Kirschen DG, et al. The visual function of professional baseball players. *Am J Ophthalmol* 1996;122:476–485.
27. Elliott DB, Yang KC, Whitaker D. Visual acuity changes throughout adulthood in normal, healthy eyes: Seeing beyond 6/6. *Optom Vis Sci* 1995;72:186–191.
28. Hoffman LG, Polan G, Powell J. The relationship of contrast sensitivity functions to sports vision. *J Am Optom Assoc* 1984;55:747–752.
29. Kirschen DG, Laby DM, Kirschen MP, et al. Optical aberrations in professional baseball players. *J Cataract Refract Surg* 2010;36:396–401.
30. Applegate RA, Donnelly WJ 3rd, Marsack JD, et al. Three-dimensional relationship between high-order root-mean-square wavefront error, pupil diameter, and aging. *J Opt Soc Am A Opt Image Sci Vis* 2007;24:578–587.
31. US Trends in refractive surgery; 2009 ISRS survey. 2009. Available at: http://www.aao.org/isrs/resources/trendssurvey.cfm. Accessed October 8, 2010.
32. Scerra C. More top athletes undergoing LASIK to improve vision. *Ophthalmol Times* 1999;24:1.
33. Laby DM, Kirschen DG, De Land P. The effect of laser refractive surgery on the on-field performance of professional baseball players. *Optometry* 2005;76:647–652.
34. Bailey MD, Olson MD, Bullimore MA, et al. The effect of LASIK on best-corrected high-and low-contrast visual acuity. *Optom Vis Sci* 2004;81:362–368.
35. Marcos S, Barbero S, Llorente L, et al. Optical response to LASIK surgery for myopia from total and corneal aberration measurements. *Invest Ophthalmol Vis Sci* 2001;42:3349–3356.
36. Keir NJ, Simpson T, Jones LW, et al. Wavefront-guided LASIK for myopia: Effect on visual acuity, contrast sensitivity, and higher order aberrations. *J Refract Surg* 2009;25:524–533.
37. Berntsen DA, Barr JT, Mitchell GL. The effect of overnight contact lens corneal reshaping on higher-order aberrations and best-corrected visual acuity. *Optom Vis Sci* 2005;82:490–497.
38. Applegate RA, Applegate RA. Set shot shooting performance and visual acuity in basketball. *Optom Vis Sci* 1992;69:765–768.
39. Mann DL, Abernethy B, Farrow D. The resilience of natural interceptive actions to refractive blur. *Hum Mov Sci* 2010;29:386–400.
40. Mann DL, Ho NY, De Souza NJ, et al. Is optimal vision required for the successful execution of an interceptive task? *Hum Mov Sci* 2007;26:343–356.

41. A randomized trial of atropine vs. patching for treatment of moderate amblyopia in children. *Arch Ophthalmol* 2002;120:268–278.
42. Trachtman JN. Biofeedback of accommodation to reduce functional myopia: A case report. *Am J Optom Physiol Opt* 1978;55:400–406.
43. Randle RJ. Responses of myopes to volitional control training of accommodation. *Ophthalmic Physiol Opt* 1988;8:333–340.
44. Balliet R, Clay A, Blood K. The training of visual acuity in myopia. *J Am Optom Assoc* 1982;53:719–724.
45. Gilmartin B, Gray LS, Winn B. The amelioration of myopia using biofeedback of accommodation: A review. *Ophthalmic Physiol Opt* 1991;11: 304–313.
46. American Academy of Ophthalmology. Complementary therapy assessment: Visual training for refractive errors. 2004. Available at: http://one.aao.org/ce/practiceguidelines/therapy content.aspx?cid=d7238b2b-a59f-49f6-9f30-64d1e84efc3b. Accessed January 26, 2011.
47. Kelly SA, Goldberg SE, Banton TA. Effect of yellow-tinted lenses on contrast sensitivity. *Am J Optom Physiol Opt* 1984;61:657–662.
48. Collins R.Outdoor measurement of visual function using maxsight contact lenses. *Am Acad Optom* [Abstract-060019], 2006.
49. Porisch E. Football players' contrast sensitivity comparison when wearing amber sport-tinted or clear contact lenses. *Optometry* 2007;78:232–235.
50. Erickson GB, Horn FC, Barney T, et al. Visual performance with sport-tinted contact lenses in natural sunlight. *Optom Vis Sci* 2009;86:509–516.
51. Kopp J. Eye on the ball: An interview with Dr. C. Stephen Johnson and Mark McGwire. *J Am Optom Assoc* 1999;70:79–84.
52. Li R, Polat U, Makous W, et al. Enhancing the contrast sensitivity function through action video game training. *Nat Neurosci* 2009;12:549–551.
53. Epelbaum M, Milleret C, Buisseret P, et al. The sensitive period for strabismic amblyopia in humans. *Ophthalmology* 1993;100:323–327.
54. Polat U, Ma-Naim T, Belkin M, et al. Improving vision in adult amblyopia by perceptual learning. *Proc Natl Acad Sci USA* 2004;101:6692–6697.
55. Wood JM, Abernethy B. An assessment of the efficacy of sports vision training programs. *Optom Vis Sci* 1997;74:646–59.
56. Barrett BT. A critical evaluation of the evidence supporting the practice of behavioural vision therapy. *Ophthalmic Physiol Opt* 2009;29:4–25.

