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Neural and optical limits to visual performance in myopia

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Abstract

We investigated the relative importance of neural and optical limitations to visual performance in myopia. A number of visual performance measures were made on all or subsets of 121 eyes of emmetropic and myopic volunteers aged 17–35 years. These tests included visual measures that are mainly neurally limited (spatial summation out to ±30° in the horizontal visual field and resolution acuity out to ±10° in the horizontal visual field) and central ocular aberrations. We found that myopia affected the neurally limited tests, but had little effect on central higher order aberration. The critical area for spatial summation increased in the temporal visual field at 0.03 log units/dioptre of myopia. Resolution acuity decreased at approximately 0.012 log units/dioptre of myopia. Losses of visual function were slightly greater in the temporal than in the nasal visual field. The observed visual deficit in myopia can be explained by either global retinal expansion with some post-receptor loss (e.g. ganglion cell death) or a posterior polar expansion in which the point about which expansion occurs is near the centre of the previously emmetropic globe.

Keywords: Aberrations; Myopia; Neural limits; Optics of the human eye; Refractive error; Spatial summation; Visual performance

1. Introduction

1.1. Visual performance

Myopia occurs because of a mismatch between the length of an eye and its power, such that either the length can be considered to be too long for the power, or the power can be considered to be too high for the length. Although population studies have found some changes in the other ocular parameters with increase in myopia, including anterior corneal radius of curvature (Atchison, 2006; Budak, Khater, Friedman, Holladay, & Koch, 1999; Carney, Mainstone, & Henderson, 1997; Goh & Lam, 1994; Goss, Van Veen, Rainey, & Feng, 1997; Grosvenor & Scott, 1991, 1994; Sheridan & Douthwaite, 1989; Stenstrom, 1948), anterior corneal asphericity (Carney et al., 1997), and anterior chamber depth (Carney et al., 1997; Grosvenor & Scott, 1991; Stenstrom, 1948), the dominant ocular (and optical) feature is the increasing vitreous chamber depth (Bullimore, Gilmartin, & Royston, 1992; Grosvenor & Scott, 1991, 1993, 1994; McBrien & Millodot, 1987; Stenstrom, 1948).

When myopic eyes are fully corrected by ophthalmic lenses and spectacle magnifications (Atchison, 1996) are taken into account (negative spectacle lenses to correct myopia reduce retinal image size), some studies but not others, have found reductions in visual performance. For resolution acuity, Chui, Yap, Chan, and Thibos (2005) found reductions with myopia in central and peripheral vision (although not significant for the former), while Coletta and Watson (2006) found non-significant reductions in resolution acuity out to 10° in the nasal visual field. For high contrast visual acuity, Strang, Winn, and Bradley (1998) found decreases at a rate of 0.011 logMAR/dioptre of myopia, but Bradley, Hook, and Haeseker (1991) found no effects. For the contrast sensitivity function, Thorn, Corwin, and Comerford (1986) and Collins and Carney (1990) found no effect of myopia while Liou and Chiu (2001) found losses for a highly myopic group (>12 D)

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for which pathological processes might be expected to be manifest.

Although it might seem reasonable to directly compare visual performances of emmetropes and corrected myopes as long as compensation is made for ophthalmic magnification, the assumption of an increase in axial length without any other changes to the ocular optics or to the retinal anatomy (e.g. no retinal stretching affecting the foveal region) means that corrected myopes should then have better resolutions than emmetropes. This is because a particular spacing on the retina should correspond to smaller angles in object (visual) space as myopia increases. This can be taken into account by calculating retinal resolution in cycles/mm based on refraction and ocular parameters. However, if the ocular parameters are not known, Knapp's law can be invoked. This law is that an axially ametropic eye with a spectacle lens placed at its anterior focal point has the same retinal image size as that of a standard emmetropic eye. Most spectacle lenses are placed near this point, 16–17 mm in front of the eye's anterior principal plane (about 1.5 mm inside the eye). Accordingly, the raw spatial visual performance results can be used (e.g. resolution in cycles/degree) when myopic subjects wear spectacles, leaving the data uncorrected for spectacle magnification because the retinal image minification from spectacles will be compensated perfectly by increased axial length. Results obtained with contact lens correction will need to be adjusted to higher spatial frequencies to simulate the optical minification that would have occurred if spectacles had been worn. We refer to this as "spectacle corrected visual space."

When either retinal resolution or spectacle corrected visual space results are used, the changes in visual performance with myopia mentioned above become more marked and where changes were not found with contact lenses they sometimes became significant with spectacle lenses. Concerning resolution acuity and referencing this to the retina, in Chui et al.'s study (2005) the foveal as well as the peripheral losses in visual acuity became significant with changes between 0.009 and 0.019 log unit/D of myopia, while Coletta and Watson (2006) found significant effects at fixation and 10° in the nasal visual field, with rates of change of 0.013 and 0.015 log unit/D of myopia (but no effect at 4° in the nasal visual field). Concerning high contrast visual acuity, Bradley et al. (1991) did not distinguish between contact lens and spectacle corrections in their subjects, so it is not known whether this would have mattered. For the contrast sensitivity function, Collins and Carney (1990) and Liou and Chiu (2001) found losses in moderate myopes wearing spectacle lenses that had not been there in a contact lens wearing group, Fiorentini and Maffei (1976) found considerable contrast sensitivity losses in spectacle corrected subjects, and Jaworski, Gentle, Zele, Vingrys, and McBrien (2006) found losses in a highly myopic group (mean correction -10 ± 1 D) compared with an emmetropic group, when spatial frequency results were referenced to the retina, beyond 18 cycles/mm.

For other visual performance measures other than visual acuity and contrast sensitivity, Jaworski et al. (2006) found reduced contrast sensitivity at the critical spot size in a spatial summation experiment for their highly myopic group as compared with an emmetropic group. Ito, Kawabata, Fujimoto, and Adachi-Usami (2001) found that frequency doubling perimetry was not different between groups consisting of emmetropes and low myopes (-1.16 D $\pm$ 0.23 D), intermediate myopes (-4.05 ± 0.17 D), and high myopes (-8.12 ± 0.36 D) (correction modality not specified). In terms of retinal responses, Kawabata and Adachi-Usami (1997) reported reduced and delayed responses in the multifocal electroretinograms (mfERGs) of myopes and Chen, Brown, and Schmid (2006) found a delayed response in the mfERGs of myopes.

1.2. Models of myopia elongation

Myopia may be classified in terms of where the myopic elongation occurs: equatorial (peripheral) expansion (Van Alphen, 1986), posterior pole (central) elongation (Sorsby, Sheridan, & Leary, 1961), or global expansion (both central and peripheral) (Cheng et al., 1992). The equatorial expansion model was invoked above when we argued that it might be expected that vision should improve as myopia increases.

In relation to eye dimensional changes in myopia, a recent magnetic resonance imaging study of 87 emmetropic and myopic eyes up to 12 D has found a variety of different eye shapes (Atchison et al., 2004). Within considerable inter-individual variation, with increase in myopia eyes increased in size both horizontally and vertically as well as axially in the approximate ratios of 1:2:3. Vertically, similar numbers of myopic eyes fitted an equatorial expansion model (combining both equatorial expansion and posterior pole elongation models) and a global expansion model, while horizontally many more eyes fitted the equatorial expansion model than the global expansion model (Atchison et al., 2004). A qualitative analysis of retinal shape showed no obvious evidence of posterior polar elongation for any subjects (Atchison et al., 2005).

Williams (1985) calculated that the resolution limit imposed by the retina of emmetropic eyes at their foveolas was 56 cycles/deg. He based his approximation on a centre-to-centre foveal cone spacing of 3 μm and on 0.29 mm of the retina corresponding to 1° of visual space. Strang et al. (1998) predicted how the "neural" resolution limit might change in myopic eye models, based on Emsley's reduced schematic eye. Assuming a fixed optical performance cut-off of 50 cycles/deg, the posterior polar expansion and global stretching models predicted that central resolution will be neurally rather than optically limited for myopic refractive errors above 3 D and 7 D of myopia, respectively. This should manifest as aliasing, in which the presence of a stimulus pattern can be detected but it cannot be resolved correctly (e.g. Thibos, Still, & Bradley, 1996).