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Adaptive optics without altering visual perception

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ABSTRACT

Adaptive optics combined with visual psychophysics creates the potential to study the relationship between visual function and the retina at the cellular scale. This potential is hampered, however, by visual interference from the wavefront-sensing beacon used during correction. For example, we have previously shown that even a dim, visible beacon can alter stimulus perception (Hofer et al., 2012). Here we describe a simple strategy employing a longer wavelength (980 nm) beacon that, in conjunction with appropriate restriction on timing and placement, allowed us to perform psychophysics when dark adapted without altering visual perception. The method was verified by comparing detection and color appearance of foveally presented small spot stimuli with and without the wavefront beacon present in 5 subjects. As an important caution, we found that significant perceptual interference can occur even with a subliminal beacon when additional measures are not taken to limit exposure. Consequently, the lack of perceptual interference should be verified for a given system, and not assumed based on invisibility of the beacon.

1. Introduction

Adaptive optics correction of the eye's aberrations allows imaging and presentation of visual stimuli with spatial detail as fine as single retinal receptors (as described first by Liang, Williams, & Miller, 1997; and as reviewed recently in Rossi et al., 2011), creating the potential to probe the neural limits on vision and the relationship between visual function and the retina at this same scale (e.g. Hofer, Singer, & Williams, 2005; Makous et al., 2006; Rossi & Roorda, 2010; Sincich et al., 2009). However, this potential is hampered by visual interference from the wavefront-sensing beacon used during correction of aberrations. To reduce this interference, most current vision science adaptive optics systems use near infrared wavefront-sensing beacons, ranging from ~780–850 nm (e.g. Artal et al., 2010; Chen et al., 2007; Guo, Atchison, & Birt, 2008; Guo et al., 2012; Li et al., 2009; Murray et al., 2010; Rossi & Roorda, 2010; Sawides et al., 2011). However, even at these wavelengths, the required powers (~5–65 μW at the cornea) are high enough that the beacon is visible and disruptive in most psychophysical tasks.

Two strategies are commonly used to mitigate the impact of the beacon. One is to turn it off after the initial aberration correction, leaving the mirror static during stimulus trial blocks (e.g. Dalimier, Dainty, & Barbur, 2008; Liang, Williams, & Miller, 1997; Marcos et al., 2008; Yoon & Williams, 2002). While this strategy completely avoids interference from the beacon, such static, or 'open-loop', aberration correction is suboptimal (Diaz-Santana et al., 2003; Hofer et al., 2001a; Hofer et al., 2001b) and not sufficient for evaluating the finest retinal and neural limits on visual function.

Another strategy is to correct aberrations dynamically with the beacon displaced from the location of the visual stimulus (e.g. Chen et al., 2007; Dalimier & Dainty, 2010; Guo, Atchison, & Birt, 2008; Hofer, Singer, & Williams, 2005). While this strategy allows excellent optical correction, so long as the distance between the beacon and stimulus is on the order of 1° or less (Bedggood et al., 2008), even a dim, displaced beacon can significantly impact perception. For example, Hofer et al. (2012) found that a 1 μW, 840 nm beacon caused significant shifts in red-green appearance for small point stimuli, similar to those previously described for large stimuli when using colored fixation targets (Jameson & Hurvich, 1967).

Here we describe a simple strategy for eliminating the impact of the wavefront-sensing beacon on both detection and perception of visual stimuli that requires only minimal changes to the standard

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system configuration, namely replacing the wavefront-sensing beacon with a longer wavelength source. Interestingly, when testing this modified system configuration, we discovered that the beacon can still interfere with the perceived appearance of visual stimuli, even when dim enough that subjects say they are unable to see it. While investigators should be aware of this potential interference, we've found it can be eliminated with careful restriction on beacon exposure and placement.

2. Methods

2.1. Wavefront sensor and adaptive optics system

We modified an existing adaptive optics system (Hofer et al., 2012) to accommodate a long wavelength 980 nm beacon (super luminescent diode, SLD, QPhotonics LLC) instead of the original, more typical, 840 nm beacon (SLD, Volga Technology Ltd.). Fig. 1 describes the current system.

The beacon wavelength was intended to be long enough to not disturb or impact vision, yet short enough for accurate wavefront sensing and correction with our existing wavefront camera. (Wavefront sensing accuracy decreases with wavelength despite the relative constancy of the eye's higher order aberrations (Fernandez & Artal, 2008), due to the effects of increased scatter and diffraction on the localizability of the Shack-Hartmann spots.) Therefore, we considered the following factors: the quantum efficiency of the existing wavefront sensing camera (PhotonMAX 512, Princeton Instruments, Trenton, NJ – Fig 2), the eye's spectral sensitivity (Baylor, Nunn, & Schnapf, 1987; Fig 2), and the increase in Shack-Hartmann spot position error as spot size increases with diffraction at longer wavelengths, Hardy, 1998).

We estimated visual and wavefront sensor sensitivity at longer wavelengths from measurements of the dark-adapted visual threshold for a continuously viewed 840 nm beacon (two subjects, method of adjustment) and the minimum power required for satisfactory adaptive correction, given the following assumptions:

1. Retinal reflectance (Berendschot et al., 2010) and ocular transmittance (Boettner & Wolter, 1962) are relatively constant with wavelength in this regime.
2. Visual threshold decreases 2.3 log units per 100 nm (extrapolated from Baylor, Nunn, & Schnapf, 1987).
3. Higher order ocular aberrations are relatively constant with wavelength (Fernandez & Artal, 2008).
4. A proportional increase in beacon power with wavelength offsets the impact of increased Shack-Hartmann spot position error maintaining a constant wavefront sensor signal to noise ratio.

While some of these assumptions are simplistic, we considered them a reasonable starting point given the level of uncertainty associated with several of the relevant factors. For example, the relative balance of visual and wavefront sensor sensitivity depends on both ocular transmission and retinal reflectance. While ocular transmission is known to vary with wavelength, with a relatively narrow dip in transmission near 980 nm and then decreasing more sharply after ~1300 nm (Boettner & Wolter, 1962), the behavior of retinal reflectance is less clear, with previous data suggesting both increases and decreases with longer wavelengths, perhaps depending on the level of pigmentation (e.g. Elsner et al., 1996; van de Kraats, Berendschot, & van Norren, 1996; Zagers et al., 2002). The role of retinal reflectance is further complicated as the penetration depth increases with wavelength, resulting in reflection from multiple layers, which may impact both wavefront sensitivity and visual sensitivity.

Fig. 2 shows the estimated thresholds of the human eye and our adaptive optics system incorporating these assumptions for near infrared wavelengths. The point where the adaptive optics system sensitivity function crosses the human eye sensitivity function, ~980 nm, is the shortest beacon wavelength predicted to allow accurate wavefront sensing without being visible to a dark-adapted subject.

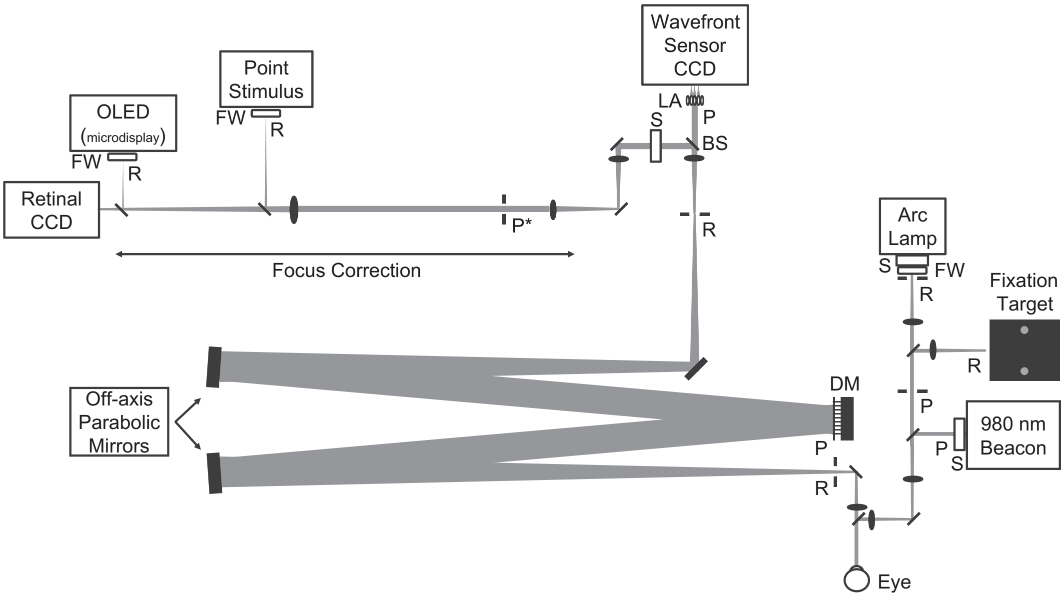

Fig. 1. Adaptive optics system for psychophysics and imaging. Aberrations are measured and corrected in closed-loop with a Shack–Hartmann wavefront sensor consisting of a thermoelectrically-cooled, electron-multiplying, charge-coupled device (EMCCD) camera (PhotonMax 512, Princeton Instruments) and a 24 mm focal length micro-lenslet array (Adaptive Optics Associates), coupled with a 97-channel deformable mirror (Xinetics). Lenslet spacing is 0.4 mm and the clear aperture of the deformable mirror is 7.26 mm in the pupil plane. The beam splitter (BS, top right) transmits infrared light for wavefront sensing (>900 nm) and reflects visible light for imaging or stimulus display. Computerized shutters (S) in pupil conjugate planes (P) control timing and exposure duration of all light sources. During adaptive optics psychophysics and retinal imaging pupil (P*) is set at 6 mm. To reduce defocus measured at the wavefront sensing camera subjects use a stabilizing bitebar mounted on a translating Badal optometer (eye, bottom right). Longitudinal chromatic aberration between wavefront-sensing and stimulus/imaging wavelengths is corrected by adjustment of a focus correction slider (upper left). Fixation target (far right) and stimuli (OLED or point stimuli) are seen through Maxwellian view with unit and 3.33 magnification, respectively.