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Accounting for the phase, spatial frequency and orientation demands of the task improves metrics based on the visual Strehl ratio

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ABSTRACT

Advances in ophthalmic instrumentation have allowed high order aberrations to be measured *in vivo*. These measurements describe the distortions to a plane wavefront entering the eye, but not the effect they have on visual performance. One metric for predicting visual performance from a wavefront measurement uses the visual Strehl ratio, calculated in the optical transfer function (OTF) domain (VSOTF) (Thibos et al., 2004). We considered how well such a metric captures empirical measurements of the effects of defocus, coma and secondary astigmatism on letter identification and on reading. We show that predictions using the visual Strehl ratio can be significantly improved by weighting the OTF by the spatial frequency band that mediates letter identification and further improved by considering the orientation of phase and contrast changes imposed by the aberration. We additionally showed that these altered metrics compare well to a cross-correlation-based metric. We suggest a version of the visual Strehl ratio, $\mathrm{VS}_{\mathrm{combined}}$, that incorporates primarily those phase disruptions and contrast changes that have been shown independently to affect object recognition processes. This metric compared well to VSOTF for letter identification and was the best predictor of reading performance, having a higher correlation with the data than either the VSOTF or cross-correlation-based metric.

1. Introduction

The first potential limitation to visual performance is that imposed by the optical components of the eye. Imperfections in these components distort the wavefront of light entering the eye and cause degradations to the image that they form on the retina. It is possible to measure the ocular wavefront error but there is no simple link between wavefront error and impairments in visual performance. Our aim in this paper is to compare wavefront-based metrics of visual image quality with performance on two tasks (letter identification and reading). We seek to improve predictions by understanding the type of information captured by the metric and the specific requirements imposed by different visual tasks.

An improved understanding of the link between wavefront error and visual impairment has clear benefits for clinical practice, both in characterising the extent of functional impairment and in considering possibilities of correction. While it is possible to provide a static, open-loop correction of the higher order aberrations of the eye for the purposes of improving vision (Chen et al., 2007; Gao et al., 2009; Jeong & Yoon, 2006; López-Gil et al., 2002, 2003; Marsack et al., 2002, 2007; Marsack, Parker, & Applegate, 2008; Navarro et al., 2000; Netto, Dupps, & Wilson, 2006; Sabesan et al., 2007; Yoon et al., 2004), this is difficult and residual aberrations may still remain. To assess the potential benefit of correcting the wavefront we need to know how to translate a wavefront measurement into real-life performance changes. Also, it is possible to accidentally introduce aberrations (see Applegate & Howland, 1997, for example) and it is important to understand the potential impairments this may cause.

1.1. Predicting visual performance from a wavefront measurement

Current metrics designed to predict visual performance from wavefront measurements fall into two broad categories; those that use an optical quality metric, such as the visual Strehl ratio (Cheng, Thibos, & Bradley, 2003; Thibos et al., 2004), and those that perform a template-matching analysis, such as the cross-correlation method derived by Watson and Ahumada (2008) or the Bayesian model introduced by Nestares, Navarro, and Antona (2003) and further developed by Dalimier and Dainty (2008) and Dalimier et al. (2009). The cross-correlation model implements template-matching explicitly and the Bayesian model implements it by decomposing the image into spatial frequency and orientation

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channels. In the next two paragraphs we briefly discuss template matching (via a cross-correlation), and compare this approach to a range of visual Strehl ratio metrics. In later sections, we consider possible improvements to metrics that are based on the visual Strehl ratio.

1.2. Cross-correlation

We have previously employed a template-matching technique based on cross-correlation. In this paper we use this metric for comparison since it has worked well in predicting impairments in reading performance (Young et al., 2011) and the increase in log contrast threshold for letter identification (Young, Love, & Smithson, 2013). Cross-correlation based methods can give predictions of performance for specific stimuli, taking their size and spatial relationships into account. One limitation is that this method gives low values for aberration-induced transformations that change the spatial extent of a letter but maintain geometric similarity. In these conditions spatial overlap is reduced but many letter features (e.g. closed forms and intersections) are preserved and visual performance may not be as impaired as the metric would suggest. A cross-correlation model is likely to perform well for predicting performance outcomes using specific sets of stimuli but it is not the most efficient method for predicting real-life performance since it must necessarily be repeated for every stimulus that an individual will encounter. For text this would mean every letter, symbol and number, in a variety of fonts. Although acuity measures also vary with font, for example, a more efficient, but perhaps less accurate, metric would be one that does not take the specific stimulus into account. The visual Strehl ratio, which we describe in the next section, is one such metric.

1.3. Computational optics and the visual Strehl ratio

For spatially incoherent light, the point spread function (PSF) of an optical system is the squared modulus of the Fourier transform of its complex pupil function, where the wavefront is the phase of that pupil function. Howland and Howland (1977) were the first to describe this wavefront error by a set of orthogonal basis functions called Zernike polynomials, which have been standardised for ophthalmology (ANSI Z80.28, 2010; ISO 24157, 2008; Thibos et al., 2000). In our experiments we have tested the effects of three Zernike modes; defocus $\left(Z_2^0\right)$, coma $\left(Z_3^1\right)$ and secondary astigmatism $\left(Z_4^2\right)$.

The PSF is real-valued and quantifies the appearance of a point source imaged through the system. The OTF, which is the Fourier transform of the PSF, quantifies how spatial frequencies are transmitted by the system and is therefore suitable for analysing the effects of aberrations on extended objects. The OTF is complex and can be split into its magnitude components, (modulation transfer function, MTF) and phase components (phase transfer function, PTF):

$$\mathrm{OTF} = \mathrm{MTF}\, e^{i\mathrm{PTF}}. \tag{1}$$

Alternatively the OTF can be considered in terms of its real and imaginary parts,

$$\mathrm{OTF} = \mathrm{MTF}\mathit{cos}(\mathrm{PTF}) + i\mathrm{MTF}\mathit{sin}(\mathrm{PTF}). \tag{2}$$

Strehl ratio is defined as the ratio of the peak value in the aberrated PSF to the equivalent value in a diffraction-limited PSF. The visual Strehl ratio compares the OTF of a system with its diffraction-limited equivalent. The strength of visual-Strehl-ratio-based metrics is that they also attempt to take visual processing factors into account. This is done by using a frequency-dependent weighting of the OTF according to the neural contrast sensitivity function (NCSF). Thibos et al. (2004) tested 33 metrics for predicting subjective refraction from wavefront measurements of which 10 were calculated using the OTF. Marsack, Thibos, and Applegate (2004) and Cheng, Bradley, and Thibos (2004) also used these same metrics to predict visual performance. All three studies agreed that the best of these metrics for predicting visual performance from the wavefront measurement was the visual Strehl ratio computed in the OTF domain (VSOTF). Other studies have also found good correlation between visual Strehl ratio-based metrics and visual acuity (Buehren & Collins, 2006; Bürhen et al., 2009; Legras & Rouger, 2008; Shi et al., 2011; Tarrant, Roorda, & Wildsoet, 2010) and Ravikumar, Sarver, and Applegate (2012) additionally showed that this correlation is independent of pupil size.

The OTF is a 2-D complex function and the VSOTF reduces this to a single value by only using the real part and integrating over frequency. For a real-valued PSF the negative frequency components of its OTF are complex conjugates of their positive counterparts. Therefore calculating the VSOTF by integrating the imaginary part of the OTF over all frequencies would give a value of zero. It should be noted that for even aberrations, such as defocus, the OTF is entirely real, causing phase shifts of either 0° or 180°. However this is not true for odd aberrations, such as coma, that cause phase shifts between 0° and 180° and so have a non-zero imaginary part. Using the real part of the OTF assumes a cosine-phase weighting on the influence of contrast changes (see Eq. (2)). For even aberrations this produces a weighting of ±1 but for odd aberrations the weighting lies between -1 and 1. Phases of 90° or 270° contribute a weighting of 0 to the real part of the OTF, losing any information about the contrast of these components. Additionally, negative weighting on the real part of the OTF implies that contrast at those frequencies impairs perception beyond the effect of removing contrast, and has the consequence that the VSOTF is not bounded between 0 and 1.

It is perhaps more appropriate to examine phase and contrast separately rather than use the real part of the OTF, which in itself is not a physically measurable or visually relevant quantity. Our intention is not simply to create a real, single-valued metric that incorporates phase, which could be achieved by transforming the (filtered) OTF back to the image domain and calculating a Strehl ratio based on the PSF. Instead we have incorporated phase in the metric in a way that is suggested by psychophysical estimates of the differential effects of particular phase disruptions (Ravikumar, Bradley, & Thibos, 2010). We suggest an alternative to using the real part that uses a linear phase weighting (with 0° phase shifts contributing 1 and 180° phase shifts contributing 0) multiplied by the modulation. This complements the findings of Ravikumar, Bradley, and Thibos (2010) that 180° phase shifts have a large impact on acuity for single letters, letter clusters and faces, and it also allows all modulations at phase shifts up-to 180° to contribute positively to the visual Strehl ratio. Whether a linear weighting on phase angle is appropriate for predicting visual performance is beyond the scope of this paper, although we note that other relationships did not give as a high a correlation with our data. Furthermore, as 180° phase shifts give a weighting of 0 we lose information about the effects of the contrast of these components. However, since 180° phase shifts have a significant negative effect on performance compared to smaller shifts, using this criterion as the zero-weighting value will at least capture something of this known aspect of visual performance.

1.4. The spatial frequency band mediating letter-based tasks

The benefit of the visual Strehl ratio is that it takes neural, as well as optical, effects into account. However, it does not consider the type of stimulus, as the cross-correlation-based metric does, nor the perceptual task performed with that stimulus type. We