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Human perception of visual stimuli modulated by direction of linear polarization

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ABSTRACT

This study explores both theoretically and experimentally the human perception of polarized light beyond that currently established. The radial analyser theory of Haidinger's phenomenon (HP) is used to predict the effect of observing visual stimuli comprising patterned zones characterized by orthogonal planes of linear polarization (linear polarization direction fields, LPD-fields). Any pattern can be represented as an LPD-field including optotypes and geometric forms. Simulated percepts differ from the original patterns although edges are mostly preserved. In edge-rich images a cross of attenuating contrast spanning the field of view is predicted.

The mathematical model is verified experimentally using a liquid crystal display (LCD)-based polarization modulator imaged through a tangential (azimuthal) analyser with properties complementary to a radial analyser. The LCD device is then used *in vivo* to elicit perceptual responses in human subjects. Normal humans are found to readily detect spatially and temporally modulated isoluminant spatially-isochromatic, highly polarized LPD stimuli. Most subjects match the stimuli to corresponding images of theoretically predicted percepts. In particular edge perception and the presence of the contrast cross was confirmed. Unlike HP, static patterned LPD stimuli are perceived without difficulty.

The simplest manifestation of human polarization perception is HP which is the fundamental element of an open set of stimulus-dependent percepts. This study demonstrates that humans have the ability to perceive and identify visual pattern stimuli defined solely by polarization state modulation.

1. Introduction

The ability to detect and respond to polarized light (polarization sensitivity) is widespread in the animal kingdom (reviewed in Horváth, 2014) and is sufficiently advanced in some species to have a prominent role in visual perception (Cronin et al., 2003). The characteristics of polarization sensitivity are diverse and based on different species-dependent mechanisms (Wehner, 2001).

True polarization vision has been defined as the ability to discriminate between different degrees and/or directions of linear and/or elliptical polarization (Nilsson & Warrant, 1999) combined with complex behavioural responses (Marshall & Cronin, 2011). The behavioural component to polarization vision further differentiates it from polarization sensitivity which is associated with stereotyped behavioural responses (e.g. navigation). Polarization vision exists in some cephalopods (Shashar, 2014) and arthropods in which polarization-sensitive photoreceptors and corresponding neural architecture compares and processes light polarization-specific neural activity (Heinze, 2014). The differentiation between polarization vision and sensitivity is discussed by Wehner (2014).

The current understanding of human polarization sensitivity is that it is rudimentary and limited to Haidinger's phenomenon (HP) (e.g. Helmholtz, 1924; Stanworth & Naylor, 1955). HP can be perceived by most humans with normal vision when observing a uniform field of linearly polarized white light. It appears as faint orthogonal yellow and blue hour-glass-shaped images (Haidinger's 'brushes') radiating 1–1.5° from the point of fixation (Helmholtz, 1924; Stanworth & Naylor, 1955).

Numerous explanations of HP have been proposed (reviewed in Horváth & Varjú, 2004; McGregor et al., 2014; Zhevandrov, 1995), but the radial analyser hypothesis (Helmholtz, 1924) is most generally accepted. This postulates that the yellow/dark brushes

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result from selective absorption of linearly polarized light by radially symmetric macular structures. Differences in the azimuth of linear polarization are converted into a luminance change within the anatomical layers of the macula. The luminance change is then detected by the underlying polarization-insensitive photoreceptors.

The spectral characteristics of HP correspond to the absorption of macular pigment with a well defined peak around 460 nm (Bone, 1980; Naylor & Stanworth, 1954; Vries et al., 1953). It is not seen at wavelengths >520 nm. Evidence for the role of pleochroic macular pigment in the generation of HP is strong (Bone & Landrum, 1992; Snodderly, Auran, et al., 1984; Snodderly, Brown, et al., 1984) although the precise mechanism has yet to be determined (McGregor et al., 2014).

HP fades rapidly due to temporal retinal adaptation (the Troxler effect) (Helmholtz, 1924). Visibility of HP is therefore enhanced by using a mechanically rotating polarizer and blue light when the yellow brushes appear as dark images (Stokes, 1883) perpendicular to the polarization axis and rotating against a blue background. Other ways of inducing temporal change in the homogenous polarization field include blinking and rotation of the head (eyes).

Disruption of macular architecture by diseases such as age related macular degeneration and diabetic retinopathy obliterate HP (Goldschmidt, 1950; Stanworth & Naylor, 1955). The detection of HP has therefore been proposed as a diagnostic tool. However, the use of HP in a clinical setting has been limited by its faintness, low contrast, continuously variable intensity, and the lack of availability of adequate diagnostic devices.

HP, which is generated by a uniform polarization field, is continuously variable in appearance and lacks abrupt luminance discontinuities (edges). This is not an ideal visual stimulus as the human visual system is particularly sensitive to edges in an image. We therefore hypothesise that non-uniform isoluminant, spatially isochromatic field stimuli in which there are abrupt changes in linear polarization between adjacent areas (polarization contrast) will generate a percept with luminance edges that are more readily detected than HP. In this context, spatially isochromatic refers to a constant waveband throughout the field of view. Although observed in animals (Cartron et al., 2013; Cronin et al., 2003; Pignatelli et al., 2011; Sabbah & Shashar, 2006; Shashar & Cronin, 1996) to date polarization contrast sensitivity has not been described in humans.

This study aims to advance the understanding of human perception of polarization. A mathematical model, based on radial analyser theory, is developed to predict human macular perception of isoluminant non-uniform polarization fields. The theoretical predictions are tested using a physical model which is then developed into a device for *in vivo* evaluation.

2. Theory and predictions

A mathematical model based on the transmission properties of a uniform field of monochromatic linearly polarized light through a radial analyser provides an analytic description of HP (Misson, 1993, 2003). This model is here extended to predict the appearance of non-uniform linear polarization fields when seen by human eyes with an intact macula. In the present study the polarization fields, which have a constant degree of linear polarization (p, such that $p > 90\%$) but vary in their **E**-vector azimuths (direction of polarization), will be referred to as linear polarization-direction fields (LPD-fields).

In the following discussion consistency with previous work is maintained by using the terminology of 'polarizer' and 'analyser' i.e. the first and last polarizing elements respectively in a train of optical components. The analyser is so-called because it translates ('analyzes') polarization into luminous intensity.

2.1. Radial analyser theory

The radial analyser model of HP is based on Malus' law for a perfect linear polarizing component where the normalised transmitted output intensity for a linear analyser is given by

$$I_L(\beta) = \cos^2(\beta) \quad (1)$$

where β (Fig. 1) is the angle between the plane of polarization of incident linearly polarized light (azimuth α) and the axis of the analyser (azimuth θ).

For a perfect radial analyser (n, Fig. 1) the transmitted output intensity along a radial component OR at azimuth θ from the plane of polarization is

$$I_R(\alpha, \theta) = \cos^2(\theta - \alpha) \quad (2)$$

For a non-uniform LPD field (Fig. 2), α is a function of position relative to the geometric centre of the analyser and can be expressed in Cartesian coordinates $\alpha(x, y)$, or polar coordinates $\alpha(r, \theta)$. These functions will be referred to as polarization base functions (PBF).

The general expression for light transmission at a point with radius r relative to the centre of the radial analyser and at azimuth θ anticlockwise from horizontal is

$$I_R(r, \theta) = \cos^2(\theta - \alpha(r, \theta)) \quad (3)$$

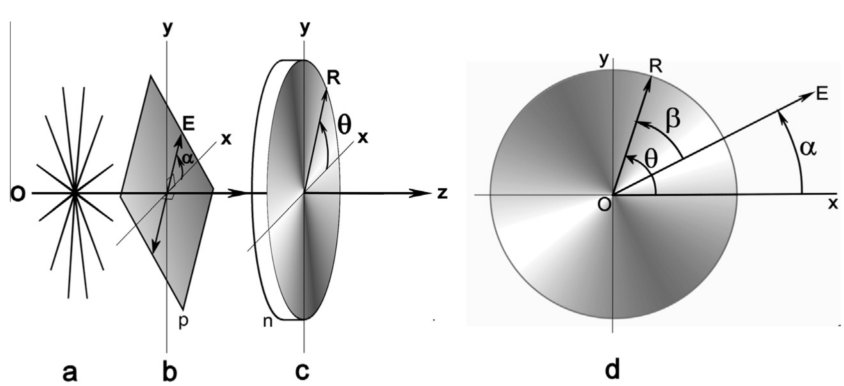

Fig. 1. Radial analyser parameters for uniform polarization field. Unpolarized light (a) travelling along the z-axis enters linear polarizer p at (b). Linearly polarized light with axis OE and azimuth α enters the radial analyser n at (c) centred on the z-axis. The azimuth of any line OR of the radial analyser is θ. (d) Intensity distribution, $I_R(\alpha, \theta)$, of light transmitted through radial analyser viewed in the x–y plane showing parameters: β is the angle between OR and OE such that $\beta = \theta - \alpha$.