A spatial property of the retino-cortical mapping

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Abstract—Striate cortex topography derives from a stretching of retinal space along the optic axis. At the retina, relative distances are preserved in a mapping of retinal space onto a spherical surface in the environment. At the cortex, relative distances along visual meridia in the cortical map are preserved in a mapping of striate cortex onto an environmental conic surface whose base is in the plane of the eye. This eco-cortical relationship can be considered a reference frame through which spatial relationships at the cortex might provide information about the environment. The present analysis provides an explanation of changes in cortical magnification with visual eccentricity in the primate and a detailed three-dimensional model of striate topography for the macaque monkey. In man, a conic environmental surface is shown to be uniformly resolvable along meridia in the visual field. Finally, the implications of this analysis of the structural properties of the retino-striate pathway and visual resolution are considered in relation to depth and distance perception.

INTRODUCTION

Classical explanations of the perception of depth and distance which can be traced through Helmholtz to Locke (Morgan, 1977) argue that the image projected onto the retina and our knowledge of the size of objects in our familiar environment are combined through a process of unconscious inference to provide our perception of a three-dimensional world. Though knowledge of the world may be of use in some circumstances we cannot have stored knowledge about the size of puddles or pebbles on a beach. As an alternative, Gibson (1950) proposed that the spatial density gradient in the retinal image projected by a uniform surface was a stimulus for distance perception. Gibson provided a specification for the direct perception of distance along surfaces like the ground but no computational theory or physiological model of how this might be achieved.

Stevens (1981) has analysed the computational difficulties in determining the layout of surfaces from texture. He points out that projected dimension depends upon both scaling (distance) and foreshortening (surface slant). Surface slant might be derived through the computation of aspect ratios of textural units (Flock, 1964) but the measurement of textural primitives is non-trivial. Particular problems arise when we consider this approach as a model for human vision, since in man stimuli of constant retinal image size appear smaller when viewed in the periphery (Newsome, 1972; Georgeson, 1980). If ‘retinal’ textural primitives are perceived correctly at some visual field locus, they will be subject to a gradient of mis-perception elsewhere, which questions whether they can be considered as providing accurate sense data for subsequent analytic mechanisms. A different approach to the problem is required.

When one looks ahead the spatial density of the projection of the ground plane onto the retina is greatest near the fovea and drops off towards the periphery. The expansion or magnification in the topographic projection of retinal space onto the surface of
striate cortex is also greatest near the fovea and drops off towards the periphery (Talbot and Marshall, 1941; Daniel and Whitteridge 1961; Van Essen et al., 1984). It is possible that the retino-cortical mapping might compensate for foreshortening and scaling under particular viewing conditions, providing an isomorphic relationship between the cortical surface and the ground. Under these conditions, distance along the environmental surface could be represented explicitly as distance along the cortical surface.

The present paper will examine this question by first discussing the structural properties of the retino-cortical mapping and alternative functional proposals. A spatial density equation will be derived and fitted to cortical magnification data to test the compensation hypothesis. The paper will then address the relationship between visual resolution and spatial density gradients before going on to describe a three-dimensional model of striate cortex and its complementary environmental surface. Finally, the utility of these geometrical relationships is discussed.

THE STRUCTURE AND FUNCTION OF THE STRIATE TOPOGRAPHIC MAPPING

The topographic, 'spatially distorted' map of the visual field on the surface of visual striate cortex (Talbot and Marshall, 1941; Daniel and Whitteridge 1961; Van Essen et al., 1984) is shown schematically in Fig. 1(a). We can see that, when flattened out, striate cortex is roughly oval with upper and lower vertical meridians forming the greater part of the boundary. The horizontal meridian for one hemi-field runs along the centre of striate cortex. There is approximately as much cortex given over to processing the central 10 deg as there is for the rest of the visual field, emphasising the prominence of the central visual field in the mapping. A description of this spatial compression achieved by the mapping with distance from the foveal representation is given by the linear cortical magnification function (Daniel and Whitteridge, 1961). This function describes the distance over the cortical surface which corresponds to one degree of visual space as a function of eccentricity in the visual field and is usually expressed as millimetres of cortex per degree of visual angle. No simple equation has been found to fit the linear inverse cortical magnification function satisfactorily (Daniel and Whitteridge, 1961). The available data, from electrophysiological studies of the primate, is either fitted closely by complex empirical functions which offer little clue to the role of the retino-cortical mapping in vision, or by simpler functions which, as a consequence, provide a poorer fit to the data.

Schwartz (1977, 1980, 1983) has offered a simple function to describe the global retino-cortical mapping and has commented on the functional significance of the mapping for visual perception. He argues for a complex logarithmic mapping of the form \( w = \log(z) \), outlined in Fig. 1(b). This function maps retinal polar coordinates, given by the complex number \( z \) in its polar form, onto a cortical rectangular coordinate space specified by the complex number \( w \) where the imaginary axis (ordinate) represents meridional angle and the real axis (abscissa) represents eccentricity. The functional hypothesis is that the logarithmic mapping has a role to play in size invariance (the ability to see an object as being the same under a transformation in size), since a logarithmic retino-cortical mapping will produce a spatial translation but no magnitude change for the cortical representation of a stimulus that increases in retinal subtense in direct proportion to retinal eccentricity. Clearly, a stimulus whose retinal image falls along an arc between the horizontal meridian and 45 deg from the vertical meridian [Fig. 1(b)] maintains the same extent under the \( \log(z) \) transformation.