Combining Modalities to Investigate Cortical Retinotopy

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Introduction

The visual cortex is often used in investigations of the human brain. The primary visual cortex, or V1, is mainly buried in the calcarine fissure, a deep sulcus which is situated on the medial surface of the occipital cortex. Virtually all information in the visual system is recognized as being processed by V1 first, and then passed out to higher order systems [1].

It is well accepted that there is a precise map of how segments of the retina are related to areas of V1. V1 has a retinotopic map in that one spot in the visual field maps directly to a spot on V1 [2]. The overall details of this map are well known from animal studies and the study of lesions in humans [3, 4]. It is agreed that more area of V1 is devoted to representing central vision rather than peripheral vision. Thus, the scale of this mapping changes as a function of retinal location. The term 'cortical magnification' [5], denoted by M, is used to describe this mapping and refers to an area of cortex that is devoted to representing a small area of visual field.

In addition, upper visual cortex receives signals from the lower visual field and similarly, lower visual cortex processes information from the upper visual field. The right visual cortex process the left field of view and vice versa. Central vision is represented at the pole of occipital cortex [3]. This general representation is referred to as the cruciform model [6].

Beyond this general agreement of this mapping, there is disagreement as to the amount of cortex that is allocated to representing central vision or other portions of the visual field [7]. There is much controversy regarding the precise details of cortical magnification and this retinotopic map. Furthermore, individual anatomical variations in the calcarine fissure seem to indicate that the cruciform model in not adequate to describe cortical retinotopy [8, 9].

Combining modalities is an ideal approach to investigate cortical retinotopy. Dipole source localization [10, 11] is one method of non-invasively determining which region of cortex is active. A neural source of magnetic and electrical activity can be modeled by a single dipole. The location of a source can then be determined by estimating a dipole that explains observed MEG or EEG data. Cortical anatomy also needs to be considered [12] and magnetic resonance (MR) images are well suited to this purpose. In order to be able to use these different modalities together effectively, a model of the visual cortex is required.

Methods

The Theoretical Model

Let the visual field be represented in polar co-ordinates (r, θ) and let the surface of the cortex be described in Cartesian co-ordinates (x, y). Cortical magnification is a function of retinal location and this relates a small area of cortex to a small area of visual field. Mathematically, this can be represented by derivatives. A small area $dxdy$ in the cortical plane corresponds to a small area of visual field $rdrd\theta$ adjusted by the cortical magnification parameter $M(r, \theta)$ [13]:

$$dxdy = M(r,\theta)rdrd\theta. \tag{1}$$

In addition, cortical magnification is a point to point mapping which transforms the visual field into its neuronal representation [14]. This means that the number of points in the retina is equivalent to the number of points in the cortex. Let $C(x, y)$ represent the density of the points in the cortex and let $\rho(r, \theta)$ represent the density in the retina. Then

$$C(x,y)dxdy = \rho(r,\theta)rdrd\theta \tag{2}$$

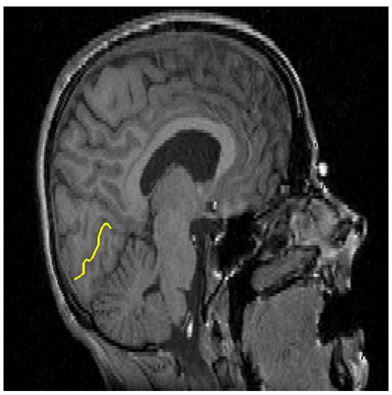
Equating (1) and (2) yields

$$M(r,\theta) = \frac{\rho(r,\theta)}{C(x,y)}, \tag{3}$$

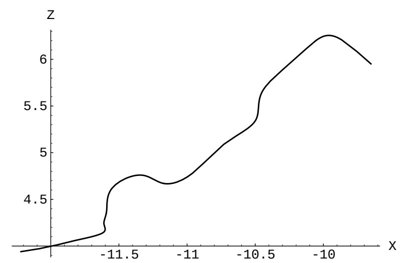
giving an expression for cortical magnification in terms of physiological properties.

The Practical Model

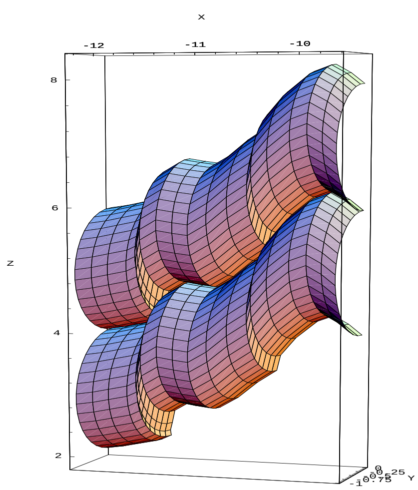
In order to incorporate cortical anatomy into the investigation of cortical retinotopy, a practical and realistic model of V1 is required. Cortical features were obtained from T1 weighted MR scans taken in a 1.5 Tesla field. Scans were taken 1.5 mm apart with contiguous spacings of 1.5 mm. Points located along the calcarine fissure were systematically extracted from the MR scans (see Fig. 1a). These points formed the basis of the model of V1.



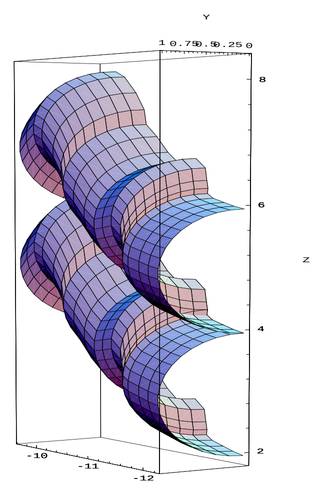
(a) MRI with Calcarine Fissure Highlighted



(b) Spline Curve which Models Calcarine Fissure



(c) Cylinder Model of V1



(d) Different Orientation of Cylinder Model

Fig. 1: Points representing the calcarine fissure were extracted from MRI data (Fig. 1a). A cubic spline was then fitted to the data (Fig. 1b). V1 is modeled by two cylinders representing the upper and lower visual cortex in one hemisphere of the brain. The cylinders lie beside each other and abut along the calcarine fissure. Since the calcarine fissure is modeled by the spline curve, the cylinders follow the realistic shape of the calcarine fissure (Fig. 1c and Fig. 1d).

Results

Cylindrical Model of Primary Visual Cortex

The points that were extracted from the MR scans were fitted to a cubic spline curve, resulting in the curve shown in Fig. 1b. As is apparent from comparing Fig. 1a and Fig. 1b, this curve approximates the shape of the calcarine fissure extremely well.

The visual cortex in one hemisphere of the brain was then modeled as two adjacent cylinders. The upper visual cortex is represented by one cylinder, as is the lower visual cortex. The two cylinders lie along side each other and abut along the length of the calcarine fissure. Since the fissure is modeled by the spline curve, the cylinders also follow the shape of the spline curve (see Fig. 1c and Fig. 1d). The result is a three dimensional cylindrical model of V1 which incorporates the realistic shape of the calcarine fissure. Fig. 1c and Fig. 1d show different orientations of this model.

Discussion

A mathematical definition for cortical magnification and a procedure for estimating human cortical magnification have been discussed in this paper. A theoretical model has been presented which is a formal and novel mathematical definition and has been obtained through new equations. By incorporating physiological properties of the point to point mapping between the visual field and the visual cortex, the concept of cortical magnification has been placed on a firmer mathematical footing.

A new and realistic model of the calcarine fissure has also been developed. The upper and lower visual cortex are modeled as two cylinders which follow the shape of the calcarine fissure. This cylinder model can now be used in conjunction with dipole source localization to estimate cortical magnification. Visual evoked potential data has been collected from a checkerboard pattern reversal experiment and the neural sources have been estimated using a dipole source localization algorithm [9]. The cylindrical model can now be used to relate the position of the estimated sources to the positions of the visual stimuli. In this manner, a truly human estimate for cortical magnification can be obtained.

The advantage of this approach is that this methodology can be applied to other areas of brain research. For example, the motor cortex and auditory cortex both have their own unique mapping [15]. By combining the modalities and techniques of dipole source localization, MEG / EEG data collection, MR images and mathematical modeling, similar approaches can be used to define and estimate a cortical mapping in these other regions.

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Acknowledgements

The authors wish to acknowledge Dr. Krish Singh of the Department of Psychology, Royal Holloway, University of London for the use of his software in displaying and presenting MR data.