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Part-based localisation and segmentation of landmark-related auditory cortical regions

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ABSTRACT

We recently presented a method for the delineation of cortical regions of interest that relies on the finite element decomposition of shape [21]. Our current work strengthens and extends the proposed technique with the following contributions: First, we provide a detailed discussion of the computational challenges related to applying the hierarchical shape modelling and energy minimisation approach to the representation and segmentation of specific areas in cortical surfaces. Second, we analyse the underlying heuristics in order to elucidate the representational power and accuracy of the a priori constrained, partial model of the auditory cortex anatomy, and improve the cortical landmark localisation. We show experimentally that a valid parametric prior can be built from expert prior knowledge in a straightforward manner. By employing the advantages of the hierarchical shape decomposition, the model can be substantially improved on the basis of training sets, which are much smaller compared with state-of-the-art methods.

1. Introduction

The variability of the sulco-gyral patterns of the human cortex remains a challenging issue in analysing the correspondence between brain anatomy and function, e.g. using anatomical and functional magnetic resonance imaging (MRI). There is evidence from architectonic studies on post-mortem brains that at least in some regions macro-anatomical landmarks are related to the individual underlying cytoarchitectonic and thus functional organisation of the brain [3,19,28]. Therefore, annotating brain regions of interest (ROI) based on anatomical landmarks is a promising approach to overcome the problem of inter-individual variation [6,18].

The manual definition of ROI is tedious and time-consuming. Furthermore, the reproducibility in highly variable brain regions, such as the auditory cortex [46,38,43,1], is not satisfactory [36]. Hence, there has recently been increasing interest within the brain imaging community in developing image analysis methods for identifying macro-anatomical landmarks as a starting point for brain functional mapping. The popular warping methods map individual brains onto a labelled reference brain, or atlas, using image-based and geometric features to drive the registration [23,26,31,49,32,48]. For registering two different brains as closely as possible, however, many methods primarily rely on manually labelled landmarks [35,62,16,63]. Topography-based parcellation methods [30,39,52,59,7,27,41,50,64,17], use graph-based descriptions of an atlas brain and the individual cortices for identifying regions of specific functionality. Even though some of the methods provide good results, the high inter-subject variability in shape, topology and structural configurations of the macro-anatomical landmarks may prevent an automatic and semantically correct parcellation at the desired level of detail [36].

This paper aims at the detailed parcellation of the human auditory cortex (AC). Parcellation of the AC is difficult, since it includes identification of highly variable supratemporal structures, e.g. Heschl's gyrus [45,46,38], within each individual cortical hemisphere. It can be identified by the folding pattern of the grey–white matter interface (cortical surface). Hence, our method is applied to flattened cortical surfaces (flat maps, see Fig. 3), where the local curvature of the original embedding of the surface in 3D space serves as geometrical feature of the folding. This information is combined with a model that describes the morphology of Heschl's gyrus and its relation to nearby macro-anatomical landmark structures such as the major sulci (i.e. the lateral fissure and sulcus temporalis superior) that delineate the superior temporal lobe. A partial model of the AC anatomy is used first for localising these individually less discriminative folds, and then for guiding the segmentation of additional, less clear and reliable auditory landmarks (i.e. the first and second transverse sulcus). Localisation and segmentation are formulated as two optimisation tasks that match the computational model to a target flat map. The challenge is to combine the fuzzy a priori

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knowledge (e.g. Heschl's gyrus may or may not show an intermediate sulcus; it builds a variable network with the parallel sulci [7]), the large geometrical and topological variability of the folding pattern and the need for an exact localisation in an efficient way. We use a part-based approach to describe the single folds as well as their arrangement to the AC folding pattern with prototypical prior shape models. The models are constructed by employing the finite element decomposition of shape exemplars.

1.1. Related work on part-based object detection

Our part-based (i.e. multi-object) approach to the cortical parcellation problem is motivated by the fact that two brains have a similar gross-anatomical structure, but may not even be topologically alike [7,38]. To address this problem, our method is different to the brain warping approach and topography-based parcellation methods (e.g. [52,7]), who attempt to find a whole-brain mapping. Instead, our method reduces the mapping to one between a folding pattern of interest. The variability in the occurrence and morphology of the AC folds and their configuration is taken into account by providing two topologically different prior models.

Part-based approaches to scene understanding are motivated by the fact that objects appear in configurations (providing context information). Moreover, most object classes have members that are globally different, i.e. can be decomposed in different ways or into parts with different proportions, but have common morphology, i.e. share parts. In the field of medical image analysis, structural models of shape variation are mostly based on Markov random fields (MRF), i.e. the configuration of shape parts is trained from labelled example data sets and represented using a nearest-neighbour graph topology, e.g. a chain or star-shaped prior (Fig. 1a and b). MRF-based prior models were used for cortex annotation [61,27,47], segmenting skeletal structures [34,53,60] and simultaneous localisation of adjacent soft tissue regions [55], among others. Techniques that use sparse graphical models of pairwise spatial relationships between parts are so popular, because of their "natural" parametrisation. An expert must simply identify landmark points on several object exemplars, from which parametric representations of densities can be learnt. Another advantage lies in the representational flexibility, which can be exploited in efficient inference techniques, e.g. variants of belief propagation and dynamic programming [24,51,67,65]. On the other hand, these methods not only rely on the success of matching particularly those parts that are considered first in the search, but also make it difficult to handle missing or supplementary parts in cluttered scenes. This is due to the fact that long-distance dependencies, i.e. non-nearest neighbour relations, as well as object–object relationships such as "parallel to" and "contained in" cannot be captured by models that rely on the Markov property assumption. Because of the tremendous variation in the anatomy of the human cortex various local optima of the MRF energy functions may exist, and pairwise geometric constraints may be too weak for mapping of cortical regions and their annotations. Latent variables may be employed to induce more restrictive constraints on the co-variation between model features, and a full graphical model may be trained to present a strong prior. For example, Fergus et al. [25] learn a constellation model, which describes the relative part locations by a fully connected graph (Fig. 1c). Similar to the pictorial structure matching (PSM) of Felzenszwalb and Huttenlocher [24] and the Gaussian mixture model of Al-Zubi et al. [2], learning relies on the repeated observation of co-occurrences between manually specified parts in similar spatial relations. However, in contrast to the MRF-based PSM, constructing a full joint model would not only require extensive training, but also inference using the model may become intractable.

The tradeoff between model richness (representational power and accuracy) and complexity (efficiency in learning and inference) may be addressed using moderately sparse prior models [8,14,40], or hybrid models that combine a MRF structural prior with a set of a priori constrained model parameters [4] or highly discriminative part detectors [15,60], all of which require supervised learning and a special node (root of tree) for use in a sequential search. The aforementioned probabilistic techniques make idealising assumptions, e.g. a normal distribution of data and model features and mutual independence of partial matches. Often, such assumptions are inadequate, but work well most probably due to the redundancy contained in model and data. Therefore, in practice the training of idealised, generative models is preferred over discriminative learning (e.g. [66]), which is very expensive (but would allow accurately separating valid from invalid non-linear variation parameters). Approaches to part-based, a priori constrained shape representation, such as [29,22] also rely on the simplification principle. In [22], non-linear shape variation is adopted by the hierarchical decomposition of shape. Under this framework, a simple, linear prior on per-shape model parameters and part-to-part dependencies can be pre-defined at different levels of shape abstraction. As shown in [20], this approach can be used to construct a computational model of the AC anatomy that captures large amounts of inter- and intra-class variability in this cortex region from a single example data set. However, only limited experimental evaluation was provided earlier in terms of a proof-of-concept showing that the method performed significantly better than guessing the location of specific cortical folds in a target image. The results were not satisfactory in view of the practical application, because of the sensitivity of the partial model to outlying data. For rendering the deformable prototype-based recognition method more application-specific, our recent work adds basic atlas information about the absolute position of the supratemporal structures in different, coarsely registered cortices [21]. In contrast to [61,59,17,47,56], this does not require extensive training of different topographic models of cortical anatomy in order to represent all possible configurations. Instead, the supplementary pose prior model constrains the search space to a certain portion of the cortical surface containing the temporal lobe, and thereby supports the localisation of the desired auditory landmarks.

1.2. Contributions and structure

Our current work focuses on strengthening and extending the part-based parcellation technique [21] with the following

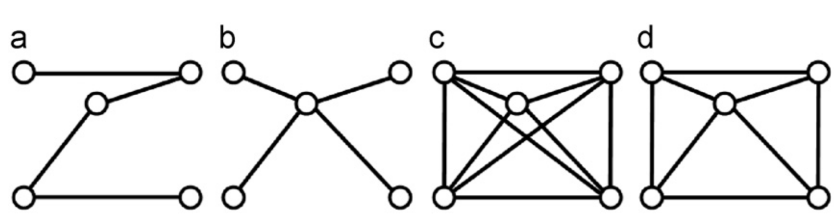

Fig. 1. Examples of geometric prior models of object structure. (a) Chain [24,60], (b) star-shaped prior [14], (c) constellation model [25], (d) a "semi-full" model, favoured in our work.