Chapter 66

The Roles of Endstopped and Curvature Tuned Computations in a Hierarchical Representation of 2D Shape

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ABSTRACT
Computational models of visual processes are of interest in fields such as cybernetics, robotics, computer vision, and others. This chapter argues for the importance of intermediate representation layers in the visual cortex that have direct impact on the next generation of object recognition strategies in computer vision. Biological inspiration - and even biological realism - is currently of great interest in the computer vision community. The authors propose that endstopping and curvature cells are of great importance for shape selectivity and show how their combination can lead to shape selective neurons, providing an approach that does not require learning between early stages based on Gabor or Difference of Gaussian filters and later stages closer to object representations.

INTRODUCTION
Over the last fifteen years, many models inspired by advances in the anatomy of the visual cortex have been presented (Cadieu, Kouch, Connor, Riesenhuber, & Poggio, 2007; Heinke & Humphreys, 2003; Murphy & Finkel, 2007; Olshausen, Anderson, & Van Essen, 1993; Riesenhuber & Poggio, 1999, 2000, 2002; E. T. Rolls & G. Deco, 2002; Serre, Wolf, Bileschi, & Riesenhuber, 2007; Wallis & Rolls, 1997). But none of the models presented until now fully explore the possible contributions of intermediate representations as are known in the brain.

In the past decade we have seen a resurgence of interest in shape representation and analysis...
in the object recognition literature. At the same time, an important number of influential studies in neuroscience have shed new light into how the brain performs the analysis of visual objects (Peissig & Tarr, 2007). Due to the latter, several models have appeared which are inspired to some degree on how neurons achieve object recognition (see the compendium of articles edited by (Dickinson, Leonardis, Schiele, & Tarr, 2009). By understanding how specific simple objects are analyzed by the brain, we may construct subsystems that emulate that behavior. 2D shapes (closed contours) are an important feature for recognizing objects (Connor, Brincat, & Pasupathy, 2007). But until recently there was no substantial proof that the biological visual system analyzes curvature in areas that are involved in the object recognition pathway, such as V4 (Pasupathy & Connor, 1999, 2002) and IT (Connor, et al., 2007).

There are several hypotheses on how, starting with neurons that may be modeled in V1 through a set of Gabor filters, we may achieve shape and object representation. We explore here one of those hypotheses, that of endstopping as an intermediate neural computation. The work of (Dobbins, Zucker, & Cynader, 1987, 1989) provides a framework where we can represent curvature from a combination of simple and complex neurons. Simple, complex, endstopped and curvature neurons are well known to exist in the visual cortex (Hubel & Wiesel, 1968; Kato, Bishop, & Orban, 1978; Pasupathy & Connor, 1999) in different areas of the object recognition pathway. Surprisingly, endstopped neurons have been neglected during the past 20 years in the modeling literature, and the models introduced up to this date achieve object representation by combining the responses of Gabor filters in different ways but not through a combination of cell responses which achieve a direct computation of curvature.

We propose here a direct way of achieving curvature and shape-selective neurons - through intermediate endstopping stages - in a biologically plausible manner which has not been explored before through the role of intermediate layers that may shed a new light into future models of human vision as well as object recognition systems.

**BACKGROUND**

**Contour and Curvature Computation in the Visual Cortex and Computer Vision**

Since the foundation of modern neuroanatomy by Ramón y Cajal (Jones, 2007; Ramon y Cajal, 1888, 1894, 1904), who gave a detailed description of nerve cell organization in the central and peripheral nervous system, great progress has been achieved in understanding the human brain.

The visual cortex is organized into different areas. V1 and V2 are the largest, each having an area of approximately 11-12% of the macaque neocortex (Felleman & Van Essen, 1991). Physiological studies show two different pathways with connections between them: The occipitotemporal pathway (V1, V2, V4, TEO and TE) is related with object recognition features (color, shape, etc.) (Logothetis & Sheinberg, 1996; Tanaka, 1996a), while the occipitoparietal pathway (V1, V2, V3, MT and MST) is associated with spatiotemporal characteristics of the scene (direction of motion, speed gradients, etc.) (Webster & Ungerleider, 1998).

Along this hierarchical architecture, neurons become increasingly selective to more complex stimuli and less sensitive to stimulus variation. At the bottom of the hierarchy, neurons in V1 are selective for edges (among other features), and at the top, TE neurons respond to complex objects with significant variation in their orientation, size, illumination and foreshortening. How is this early visual information transformed into whole objects?

Concerning orientation selection, V1 neurons can be classified into three types: simple cells, complex cells, and endstopped cells (Hubel & Wiesel, 1959, 1962, 1965, 1968):
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