Early Stages of Vision Might Explain Data to Information Transformation

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Abstract. In this paper we argue that the process of attaching meaning to data, in order to produce information, occurs at first within the early stages of the sensory areas. This hypothesis is based on an analysis of the signal flow within the early stages of vision. It is evident that the simplest form of visual information, which is an edge, is conceptualized at first within the primary visual cortex. Support for this hypothesis comes also from computational vision theories, since the simplest features that can be extracted from an image are closely related to what is represented within the primary visual cortex.

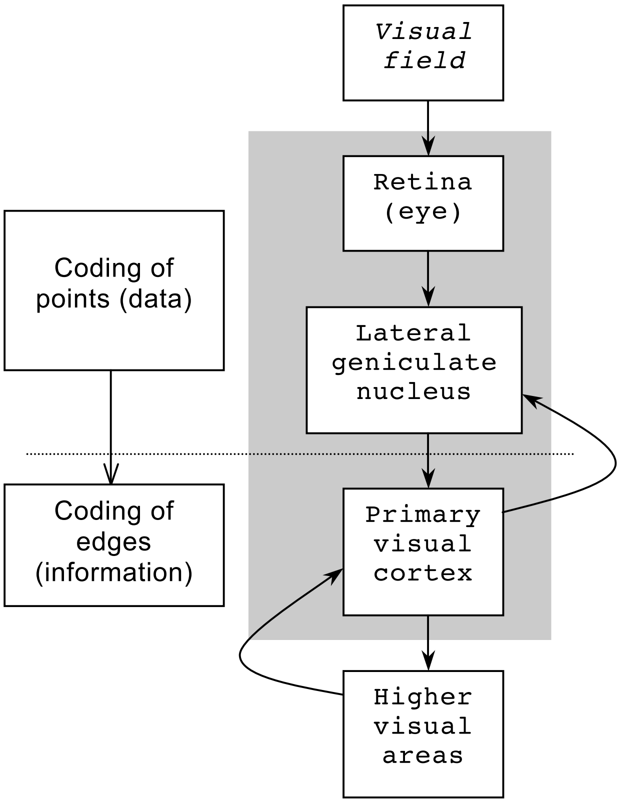
1 Introduction

It has been suggested that information is the result of attaching meaning to data [3,6,7]. According to this view data is transformed, through a chain of processes, to generate information. However, this view does not deal with the question of where, i.e. in which sub-structure of the brain, is data transformed into information. Obviously, such a transformation involves neurons, which through interactions with each other represent our memory and enable us to interact with the environment. A justifiable question is if it is possible to locate those neurons or sub-structures of the brain that lead to the data to information transformation.

The primary visual cortex (V1) is the end station of the early stages of vision and interacts heavily with higher visual areas (Fig. 1). Thus, an analysis of the activity that starts in the eyes and continues to the primary visual cortex might reveal where data is transformed to become information. Besides, this analysis is also applicable to other senses as well, since there are structural similarities between various cortical areas, which is primarily manifested by the modular and laminar organization of the neocortex (main part of the brain) [13].

In this paper we address the question of where data is transformed into information. Taking together the evidences from visual neuroscience and computational vision it is plausible to assume that the raw data that enters the eyes are transformed into meaningful information within the primary visual cortex, since the simplest form of information emerges within this structure.

Figure 1. A scheme of the signal flow within the early stages of vision (the gray area). Within



the retina and the lateral geniculate nucleus neurons have circular point-like receptive fields. Neurons that populate the primary visual cortex are selective to the orientation of the contrast-edges and lines. The vertical line illustrates the border between the regions that are dedicated to data and information.

2 Early Stages of Vision

Early stages of vision consist of three structures, i.e. the retina, the lateral geniculate nucleus (LGN), and the primary visual cortex (V1) (Fig. 1). The retina is the first processing step of the incoming signals of the visual field, since the visual field is projected to the two retinae located in each eye. The physiological studies done by Kuffler have shown that the cat retinal ganglion cells react to small spots of light [11] (Fig. 2 *Left*). This study indicates that each retinal ganglion cell responds to stimulation of a small, circular patch of the retina. This patch defines the receptive field of a single retinal ganglion cell. Kuffler has discovered two different types of retinal ganglion cells (ON and OFF) [11]. When the center of an ON retinal ganglion cell is stimulated with a light spot, the cell reacts by generating a burst of spikes as a result of increased activity. When the light stimulus, which covers the center of the ON retinal ganglion cell, is moved to the periphery of the cell's receptive field, the cell is inhibited (decreased activity). The OFF retinal ganglion cells have opposite receptive field properties. These cells prefer dark spots in the center of their receptive fields, which is surrounded by a light region. The receptive fields of the retinal ganglion cells can be mathematically described with a so-called 'Mexican-hat' function.

Note that the activity of the retinal ganglion cells depends on the contrast, i.e. the difference in the amount of light that falls on their receptive field centers and surrounds. Both types of retinal ganglion cells are equally numbered, and are distributed equally in the retina.

The major target of the retinal ganglion cells is the LGN. Neurons in the LGN send their axons to the primary visual cortex. Note that the retinotopic representation of the visual field, which emerges in the retina, is preserved throughout the retina-LGN-V1 pathway. It has been shown that the fibers that start from the neighboring retinal ganglion cells within the retina converge to neighboring geniculate cells within the LGN [10]. The geniculate cells project in turn to neighboring regions within the V1 [10] (Fig. 2).

Neurons within the LGN are classified as ON and OFF cells similar to the retinal ganglion cells. As a result the LGN is often seen as a relay between the retina and the primary visual cortex. However, the LGN also receives modulatory input from the V1.

Neurons populating the primary visual cortex react selectively to contrast-edge (line) orientations. These cells are named "simple" and "complex" depending on their response properties [9,10]. However, the relay cells within the LGN, which carry the visual signals from the retina to the primary visual cortex, are not orientation selective. It is not known in detail how orientation selectivity of the neurons within the primary visual cortex emerges [1–5,14]. Hubel and Wiesel have proposed that orientation selectivity of the cat simple cells is a consequence of the arrangement of the LGN input [9]. According to this arrangement, the ON-center LGN cells converge to ON-subregions of the simple cells (Fig. 2). The OFF-subregions of the simple cells are constructed in the same way by the OFF-center LGN cells (Fig. 2). This model is called the 'feedforward' model, since the intracortical connections do not play any prominent functional role in generating the orientation selectivity properties of the neurons within the V1. The signals flow in a pure feedforward fashion, along the retina-LGN-V1 pathway.

The simple cells, which dominate layer 4 of cat, have elongated ON- and OFF-subregions that reflect the LGN input. Hubel and Wiesel have discovered that these cells' responses to complex stimuli can be predicted from their responses to individual spots of lights [9,10]. As a consequence, a simple cell's receptive field can be mapped based on its response to small light spots positioned on different locations on the retina. A light spot, which is positioned at the cells' ON-subregion, excites the cell, whereas a light spot positioned at the cells OFF-subregion inhibits the cell. The responses to 'dark' spots are opposite to light spots.

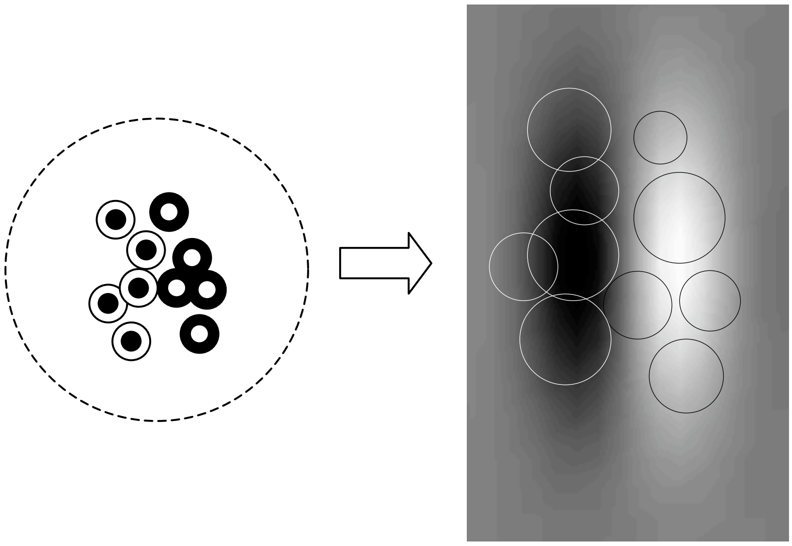


Figure 2. *Left*. An illustration, which shows the receptive fields of ten LGN (or retinal ganglion) cells. Half of them are ON-center and the rest are OFF-center neurons. Other cells that are located within this circular patch are not shown for the purpose of clarity. *Right*. An illustration showing the receptive field profile of a simple cell (located within the V1). Note that the spatial relationships between the LGN (or retinal ganglion) cells are preserved during the projections to the primary visual cortex. The receptive field profile of the simple cell is basically an effect of this preservation.

3 Computational Theories of Vision

The objective of computational vision is to process images, more precisely to detect (or classify) shapes, objects and other primitives. One of the most influential theories within this field is the primal sketch theory by Marr and Hildreth [12]. This theory addresses the detection of lines and contrast edges. Later, it has been shown that the primal sketch theory fits elegantly the Hubel and Wiesel feedforward model of orientation selectivity [9].

According to Marr and Hildreth one can transform a fully analog, grey-scale image to a symbolic representation of image-based features [12]. It was proposed that vision must go “symbolic” right at the beginning. The suggested symbols were bars, contrast edges, terminations and “blobs”. Bars (or lines) are short line segments whose terminations lie outside the receptive field. Blobs’ terminations lie within the receptive field. Terminations represent “ending of tings”.

Another theory of vision is based on the filtering of the images [8]. In this theory it is assumed that an image consists of several sinusoidal gratings with various orientations and spatial frequencies. It is further assumed that neurons that populate the primary visual cortex can be seen as spatial frequency filters. The frequency of such a filter is defined by the width of the ON- and OFF-subregions of the neuron's receptive field. Thus each neuron responds selectively to a narrow band of spatial frequencies. At first sight this way of representing an image seems to be radically different from the primal sketch theory. It is, however, obvious that a contrast-edge has both an orientation and a spatial frequency. It is thus possible to represent a contrast-edge as a sinusoidal grating, which has the width of one cycle. Consequently, it is plausible to assume that the sinusoidal gratings that are detected are as symbolic as the contrast-edges of the primal sketch theory.

4 Discussion

The short overview of the two scientific disciplines shows that the idea of transforming data to produce information is not entirely new, at least not in vision research. Independent of the main objective of these two disciplines, both neuroscientists and computational vision theorists deal with the question of how the systems that they study generate information from incoming data.

It is obvious that, at least within the brain, data is transformed into information continuously (Fig. 1). This transformation process starts at the retina and goes on all the way to the V1, and to the higher visual areas where objects are recognized (Fig. 1). However, feedback connections that emerge within the V1 and target LGN show that the image, which is registered by the eyes, is modified before it reaches the V1. This feedback path is highly interesting since it demonstrates how "more meaningful" data can modify data, which is "raw".

We hypothesize that the feedforward and feedback connections within and between the three structures that are found in the early stages of vision are doing more than passive preprocessing. Note further that when information is defined as "data that has a meaning" it is meant that information must fulfill certain requirements, i.e. information must have a meaning. In terms of vision the simplest form of meaningful information is an edge. An edge can be perceived as a border or a direction. Note that the same cells that analyze orientations of contrast-edges also represent other shapes, such as small points.

Within the early stages of vision the concept of an edge appears first in V1. Recall that neurons in the retina and the LGN analyze simply discrete points within the visual field, whereas neurons within the V1 are tuned to orientations of the edges. This transformation from a set of spatially ordered discrete points to a line is in our view the transformation of data to information.

Similarly, computational vision theories do also stress that fact that vision goes symbolic very early. Data is the pixel values (roughly corresponding to retina and LGN), whereas bars, contrast edges, terminations, blobs and spatial frequencies are the simplest forms of information. Note that all these forms of information emerge within the V1. Consequently, despite differences in approach, both the primal sketch theory and the spatial frequency filter theory assume that data is transformed into information within the V1.

Taking together the evidences from two complementary disciplines within the vision research it is plausible to assume that raw data that enters the eyes is transformed into meaningful information within the primary visual cortex, since the simplest form of information is represented at first within this structure.

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