# Neural Modeling of Flow Rendering Effectiveness

DANIEL PINEO AND COLIN WARE, University of New Hampshire
SEAN FOGARTY, University of Illinois at Urbana-Champaign

## 1. INTRODUCTION

Many techniques for 2D flow visualization have been developed and applied. These include grids of little arrows, still the most common for many applications, equally spaced streamlines [Turk and Banks 1996, Jobard and Lefer 1997], and line integral convolution (LIC) [Cabral and Leedom 1993]. But which is best and why? [Laidlaw et al. 2001] showed that the "which is best" question can be answered by means of user studies in which participants are asked to carry out tasks such as tracing advection pathways or finding critical points in the flow field. (Note: An advection pathway is the same as a streamline in a steady flow field.) [Ware 2008] proposed that the "why" question may be answered through the application of recent theories of the way contours in the environment are processed in the visual cortex of the brain. But Ware only provided a descriptive sketch with minimal detail and no formal expression. In the present paper, we show, through a numerical model of neural processing in the cortex, how the theory predicts which methods will be best for an advection path tracing task.

### 1.1 The IBQ Approach in Image Quality Estimation

The IBQ approach combined with psychometric methods has proven suitable, especially for testing the performance of imaging devices or their components and then returning this quality information to the product development or evaluation stages. When the subjective changes in image quality are multivariate, the technical parameters changing in the test image are unknown or difficult to compute. However, the IBQ approach can be used to determine the subjectively important quality dimensions with a wide range of natural image material related to changes caused by different devices or their components. In order to tune the image-processing components for optimal performance, it is important to know what the subjectively crucial characteristics that change in the perceived image quality are as a function of the tuning parameters, or simply for different components. Table I describes the problems caused by multivariate changes in image quality and offers suggestions of how to approach them by using different measurement methods that complement each other. The IBQ approach can complement the psychometric approaches and objective measurements by defining the subjective meaning of image quality attributes and characteristics; in other words, it reveals how important they are for the overall perceived quality. This information can then be used as guidance in tuning, and no complex models are needed in order to understand the relation between objective measures and subjective quality ratings.

Our basic rational is as follows. Tracing an advection pathway for a particle dropped in a flow field is a perceptual task that can be carried out with the aid of a visual representation of the flow. The task requires that an individual attempts to trace a continuous contour from some designated starting point in the flow until some terminating condition is realized. This terminating condition might be the edge of the flow field or the crossing of some designated boundary. If we can produce a neurologically plausible model of contour perception then this may be the basis of a rigorous theory of flow visualization efficiency.

## 1.2    Conditions

The reproduction of the gestures was performed in the presence or absence of visual and auditory feedback, resulting in four (2 x 2) conditions

(1)  Visual and auditory feedback (V + A).
(2)  Visual feedback, no auditory feedback (V).
(3)  Auditory feedback, no visual feedback (A).
(4)  No visual or auditory feedback (None).

The order of the four conditions was randomized across participants.

– *when + where ⇒ what: State the properties of an object or objects at a certain time, or set of times, and a certain place, or set of places.*
– *when + what ⇒ where: State the location or set of locations.*
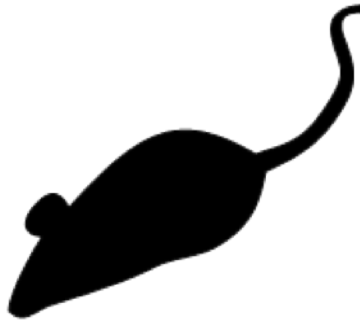– *where + what  ⇒ when: State the time or set of times.*



Fig. 1. Neurons are arranged in V1 in a column architecture. Neurons in a particular column respond preferentially to the same edge orientation. Moving across the cortex (by a minute amount) yields columns responding to edges having different orientations. A hypercolumn is a section of cortex that represents a complete set of orientations for a particular location in space.

When conducting a user study, the goal for the study is to measure the suitability of the visualization in some sense. What is actually measured is a fundamental question that we believe can be handled by using the concepts of effectiveness, efficiency, and satisfaction. These three concepts are derived from the ISO standard of usability 9241-11.

> Extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use.

The mechanisms of contour perception have been studied by psychologists for at least 80 years, starting with the Gestalt psychologists. A major breakthrough occurred with the work of Hubel and Wiesel [Hubel and Wiesel 1962, Hubel and Wiesel 1968] and from that time, neurological theories of contour perception developed. In this article, we show that a model of neural processing in the visual cortex can be used to predict which flow representation methods will be better. Our model has two stages. The first is a contour enhancement model. Contour enhancement is achieved through lateral connections between nearby local edge detectors. This produces a neural map in which continuous contours have an enhanced representation. The model or cortical processing we chose to apply is adapted from [Li 1998]. The second stage is a contour integration model. This represents a higher level cognitive process whereby a pathway is traced.

THEOREM 1.1. *For a video sequence of n frames, an optimal approach based on dynamic programming can retrieve all levels of key frames together with their temporal boundaries in O(n⁴) times.*

We apply the model to a set of 2D flow visualization methods that were previously studied by [Laidlaw et al. 2001]. This allows us to carry out a qualitative comparison between the model and how humans actually performed. We evaluated the model against human performance in an experiment in which humans and the model performed the same task.

Our article is organized as follows. First we summarize what is known about the cortical processing of contours and introduce Li's [Li 1998] model of the cortex. Next we show how a slightly modified version of Li's model differentially enhances various flow rendering methods. Following this, we develop a perceptual model of advection tracing and show how it predicts different outcomes for an advection path-tracing task based on the prior work of [Laidlaw et al. 2001]. Finally we discuss how this work relates to other work that has applied perceptual modeling to data visualization and suggest other uses of the general method.

Visual information passes along the optic nerve from the retina of the eye where it is relayed, via a set of synaptic junctions in the midbrain lateral geniculate nucleus, to the primary visual cortex at the back or the brain (Visual Area 1 or V1). It has been known since the Hubel and Wiesel's work in the 60s that the visual cortex contains billions of neurons that are sensitive to oriented edges and contours in the light falling on the retina. Such neurons have localized receptive fields each responding to the orientation information contained within the light imaged in a small patch of retina. A widely used mathematical model of a V1 neuron's receptive field is the Gabor function [Daugman 1985]:

$$Gabor(u, \ v, \ \lambda, \ \theta, \ \phi, \ \sigma, \ \gamma) = e^{-\frac{u'^2 + \gamma^2 v'^2}{2\sigma^2}} \cos(2\pi \frac{u'}{\lambda} + \phi).$$

(1)

Hubel and Wiesel [Hubel and Wiesel 1962, Hubel and Wiesel 1968] found that neurons responding to similar orientations were clustered together in a structure they called a column which extended from the surface of the visual cortex to the white matter (see Figure 1). Later, they and other researchers discovered hypercolumn structures consisting of thousands of neurons all responding to the same area of visual space and selecting for a range of orientations. Overall, V1 contains a topographic map of the visual field having the property that every part of the retinal image is processed in parallel for all orientations. These orientation selective neurons have provided the basis for all subsequent theories of contour and edge detection.

There remains the problem of how the output of orientation sensitive neurons, each responding to different parts of a visual contour, becomes combined to represent the whole contour. Part of the solution appears to be a contour enhancement mechanism. [Field et al. 1993] examined the human's ability to perceive a contour composed of discrete oriented elements. They placed a contour composed of separated Gabor patches, among a field of randomly orientated Gabor patches. Contours were detected when the patches were smoothly aligned. They were not detected when there was misalignment. This work suggests that there is some manner of lateral coupling among the visual elements involved in perceiving the Gabor patches in the contour. These researchers have suggested that similarly oriented aligned contours mutually excite one another, while they inhibit other neurons that are nearby.

## REFERENCES

Brian Cabral and Leith C. Leedom. 1993. Imaging vector fields using line integral convolution. In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH'93)*. ACM, New York, NY, 263–270. DOI:http://dx.doi.org/10.1145/166117.166151

David J. Field, Anthony Hayes, and Robert F. Hess. 1993. Contour integration by the human visual system: Evidence for a local "association field". *Vision Res.* 33, 2 (1993), 173–193. DOI:http://dx.doi.org/10.1016/0042-6989(93)90156-Q

David H. Hubel and Torsten N. Wiesel. 1962. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *J. Physiol.* 160, 1 (1962), 106–154. http://jp.physoc.org

David H. Hubel and Torsten N. Wiesel. 1968. Receptive fields and functional architecture of monkey striate cortex. (1968). http://jp.physoc.org/cgi/content/abstract/195/1/215 http://www.hubel/papers/uconn.html.

Bruno Jobard and Wilfrid Lefer. 1997. Creating evenly-spaced streamlines of arbitrary density. In *Proceedings of the Eurographics Workshop*. Springer Verlag, Berlin, 43–56.

David H. Laidlaw, J. Scott Davidson, Timothy S. Miller, Marco da Silva, R. M. Kirby, William H. Warren, and Michael Tarr. 2001. Quantitative comparative evaluation of 2D vector field visualization methods. In *Proceedings of the Conference on Visualization (VIS'01)*. IEEE Computer Society, Los Alamitos, CA, 143–150.

Zhaoping Li. 1998. A neural model of contour integration in the primary visual cortex. *Neural Comput.* 10, 4 (1998), 903–940. DOI:http://dx.doi.org/10.1162/089976698300017557

Greg Turk and David Banks. 1996. *Image-guided streamline placement*. Technical Report I-CA2200. University of California, Santa Barbara, CA. 453–460 pages. DOI:http://dx.doi.org/10.1145/237170.237285

Colin Ware. 2008. Toward a Perceptual Theory of Flow Visualization. *IEEE Comput. Graph. Appl.* 28, 2 (2008), 6–11. DOI:http://dx.doi.org/10.1109/MCG.2008.39