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13. ABSTRACT (Maximum 200 words)
During the past year these investigators: 1) Illustrated application of computer science to neuroscience at three levels: measuring, modeling, and understanding the computational function of the columnar pattern of ocular dominance in primate visual cortex; 2) Demonstrated an algorithm for modeling polymap architectures of the cerebral neocortex, where the term "polymap" emphasizes the joint occurrence of topographic mapping of multiple sub-modalities, interlaced in the form of macroscopic patches ("columns") into a single cortical lamina; 3) Considered a space-variant sensor design based on the conformal mapping of the halp disk, w=log (z+a), a 0, which characterizes the anatomical structure of the primate and human visual systems. 4) Showed that the best algorithm for fusing multiple space-variant fixations of the same scene show, under certain assumptions of pixel distribution, is indeed optimal in a least-squared-error sense; 5) Analyzed the characteristics of a synthetic sensor comparable, with respect to field width and resolution, to the primate visual system; 6) Showed a quantitative measurement of the macaque ocular dominance column pattern, based on measurement of local power spectral densities of a computer reconstruction and numerical flattening of V1.

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June 30, 1991

Dr. Gen Haddad
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Dear Dr. Haddad ,

This letter constitutes the technical report for the period June 1, 1990 -> June 1, 1991 for grant #AFOSR-88-0275. The contract period for AFOSR-88-0275 is scheduled to end on July 31,1991.

Last December, we received a letter from Dr. John Tangney who asked contractees to attempt to extend existing funding for as long as possible, due to possible funding restrictions next year at AFOSR, so that renewal applications could be pushed into next year(Copy enclosed).

Since we have made substantial progress on our work on this contract, I made provisions for extending our AFOSR support at that time by using other funding available to support part of the personnel on this contract. My intention is to finish this work over the next six months, and to write a renewal application in the fall. as per Dr. Tangney's suggestion (in December). But to do so I will require a letter of (unpaid)continuation from you so that NYU will not freeze the remaining funding on this contract. I discussed this matter with Dr. Tangney on the telephone, and he verbally approved it, but suggested that I write to you describing these plans.

If possible, it would be helpful if you wrote a note approving (in principle) this unpaid extension, since otherwise it may take a long while for it to "grind" through both the DOD and NYU beaurocracy, causing a delay in the completion of the contract. Any form of note from you would satisfy the NYU end of this, (I will need it before July 31, to avoid any problems here). I am very appreciative of any help that you can provide in this matter.

I will now briefly outline our progress during the past year by outlining our publications which have been submitted and which have appeared in print in this period. Copies of the relevant publications are enclosed with this report.

1. *Computational Neuroscience.* **Edited by Eric Schwartz. MIT Press, 1990.**

This volume, appearing in fall 1990, presents 30 chapters by various experts in computational neuroscience, with the intention of providing a working definition of this term.

2. *Visualizing and understanding patterns of brain architecture.* **Alan Rojer and Eric Schwartz. to appear in Fall 1991, NATO ASR series, " Biologically Motivated Robotic Design", edited by P. Dario and G. Sandini.**

We illustrate application of computer science to neuroscience at three levels: measuring, modeling, and understanding the computational function of the columnar pattern of ocular dominance in primate visual cortex. We review our methods for the quantitative reconstruction of the pattern of binocular input to the visual cortex of monkeys. We show that an oriented bandpass filter, applied to white noise, provides a simple parametric characterization of the observed pattern. We suggest a computational motivation for the columnar architecture as a "brain data structure" for a stereo vision algorithm based on the properties of a nonlinear filter, the cepstrum. This work illustrates some of the algorithmic difficulties and novel research problems encountered when computational approaches are used to visualize the patterns of neural architecture of the primate visual system.

3. *Computer simulation of cortical polymaps: The proto-column algorithm.* **Accepted for publication in Neural Networks(1991). Pierre Landau and Eric Schwartz**

In this paper, we demonstrate an algorithm for modeling polymap architectures of the cerebral neocortex, where the term "polymap" emphasizes the joint occurrence of topographic mapping of multiple sub-modalities, interlaced in the form of macroscopic patches ("columns") into a single cortical lamina. Examples include the ocular dominance, cytochrome oxidase puff/extra-puff, and orientation column structures of primate striate cortex, the thick-thin-interstripe columns of V-2, and the direction columns of MT. As these architectures represent the merging of information from several histological and/or featural laminae, we use the term "polymap" to describe them. The justification for this neologism is that the conventional terms "mapping" and "topographic mapping" are not sufficiently expressive of the complexity and structure of neo-cortical architecture, and their use often leads to imprecision or confusion.

The structure of polymaps raise difficult conceptual, experimental, and computational issues, and the demonstration of an algorithm for simulating them is of fundamental significance to the understanding, description, and modeling of neo-cortical functional architectures. We have found it necessary to introduce two new data structures, motivated by work in computational geometry, which have allowed us to construct a detailed algorithm for simulating polymaps.

4. *Design considerations for a space-variant visual sensor with complex logarithmic geometry.* **Alan Rojer and Eric Schwartz. Proceedings of the 10^{th} International Conference on Pattern Recognition (1990), pp. 278-285.**

Human vision is both active and space-variant. Recent interest in exploiting these characteristics in machine vision naturally focuses attention on the design parameters of a space-variant sensor. We consider space-variant sensor design based on the conformal mapping of the half disk, $w=\log(z+a)$, with real $a>0$, which characterizes the anatomical structure of the primate and human visual systems. There are three relevant parameters: the "circumferential index" κ, which we define as the number of pixels around the periphery of the sensor, the "visual field radius" R (of the half-disk to be mapped), and the "map parameter" a from above, which displaces the logarithm's singularity at the origin out of the domain of the mapping. We show that the log sensor requires $O(\kappa^2 \log(R/a))$ pixels. The pixel width in the fovea (foveal resolution) L_{fov} is proportional to a/κ. If we accept a fixed circumferential index (constant κ), the space complexity of the log sensor with respect to foveal resolution goes as $O(-\log L_{fov})$. By contrast, a uniform-resolution sensor has a space complexity that goes as $O(L_{fov}^{-2})$. Similarly, when the space complexity of the sensor is considered with respect to the field size with a fixed foveal resolution, we find that the space complexity goes as $O(\log \tilde{R})$, while for the uniform-resolution sensor, the space resolution goes as O(R^2). Using this analysis, it is possible to directly compare the space complexity of different sensor designs in the complex logarithmic family. In particular, we can obtain rough estimates of the parameters necessary to duplicate the field width/resolution performance of the human visual system.

5. *Cat and monkey cortical column patterns modeled by band-pass filtered 2D white noise.* **Biological Cybernetics 62:381-391(1990). Alan Rojer and Eric Schwartz**

A simple algorithm based on bandpass-filtering of white noise images provides good quality computer reconstruction of the cat and monkey ocular dominance and orientation column patterns. A small number of parameters control the frequency, orientation, "branchedness", and "regularity" of the column patterns. An oriented (anisotropic) bandpass filter followed by a threshold operation models the macaque ocular dominance column pattern and cat orientation column system. An unoriented (isotropic) bandpass filter models the cat ocular dominance column pattern and the macaque orientation column system. The resemblance of computer graphic simulations produced by this algorithm, and histological pattern data, is strong. Since this algorithm is very fast, we have been able to extensively explore its parameter space in order to determine filter parameters which closely match the structure of the various cortical column systems. In particular, we have applied spectral analysis to our recent computer reconstruction of the macaque ocular dominance column system, and the model produced by the present algorithm is in close agreement with this detailed data analysis.

6. *Fusion of multiple fixations with a space-variant sensor: conditional optimality of maximum-resolution blending.* **SPIE Symposium on Advances in Intelligent Systems, Program on Intelligent Robots and Computer Vision, Intelligent Robots and Computer Vision IX (1990). SPIE 1831-30, pp. 1-11. Alan Rojer and Eric L. Schwartz.**

A unimodal sensory fusion problem posed by all active vision systems is the incorporation of multiple fixations (i.e. views) to provide a coherent and stable world view. The degree of difficulty of this problem is greatly increased when **space-variant** active vision systems are considered. In such systems, in which pixel size is not invariant across the sensor, the same regions of the world will be imaged at differing resolutions in successive fixations. Methods for fusing multiple fixations with a space-variant sensor have received little analytic or computational attention. Motivatation derives from the following observations:

- High performance biological systems (cat,monkey,human) are highly space-variant.
- Construction of VLSI based space-variant machine vision systems is currently underway in several labs, including our own.
- Active vision systems based on space-variant sensors, which are likely to dominate some application areas of machine vision when available, require a solution to this problem.

In previous work by ourselves and others, it has been argued that the best algorithm for fusing multiple space-variant fixations of the same scene is to simply choose the maximum resolution information available at each position in the reconstructed scene. It is intuitively compelling that this will yield an optimal reconstruction, since it uses the highest resolution (hence most accurate) information available at each position. We can show, under certain assumptions of pixel distribution, that this algorithm is indeed optimal in a least-squared-error sense. In the presence of noise, however, optimality no longer holds; a certain degree of averaging of lower resolution information is required to obtain optimal reconstruction. We also present empirical demonstrations of fused images using both maximum-resolution and averaged blending techniqes, and we illustrate the effects of noise on the quality of reconstruction.

7. *Biological basis for space-variant sensor design I: Parameters of monkey and human spatial vision.* **SPIE Symposium on Optics Applications (1990). Eric Schwartz and Alan Rojer. SPIE 1832-14, pp. 1-13.**

Biological sensor design has long provided inspiration for sensor design in machine vision. However, relatively little attention has been paid to the actual design parameters provided by biological systems, as opposed to the general nature of biological vision architectures. In the present paper, we will provide a review of current knowledge of primate spatial vision design parameters and will present recent experimental and modeling work from our lab which demonstrates that a numerical conformal mapping, which is a refinement of our previous complex logarithmic model, provides the best current summary of this feature of the primate visual system.

8. *Biological Basis for Space-Variant Sensor Design II: Implications for VLSI Sensor Design.* **SPIE Symposium on Advances in Intelligent Systems (1990). SPIE 1386-06. pp. 1-9. Alan Rojer and Eric Schwartz.**

We analyze the characteristics of a synthetic sensor comparable, with respect to field width and resolution, to the primate visual system. We estimate that 150,000-300,000 pixels are sufficient using a logarithmic sensor geometry, and demonstrate that this calculation is consistent with known characteristics of biological vision, e.g. the number of fibers in the optic nerve. To obtain the field width and resolution of the primate eye with a uniform sensor requires between 10^3–10^4 times the number of pixels estimated for the comparable log sensor. Another interesting observation is that the field width and resolution of a conventional 512×512 sensor can be obtained with around 5000 pixels using the log geometry. We conclude with consideration of the prospects for achieving human-like performance with contemporary VLSI technology and briefly discuss progress on space-variant VLSI sensor design.

9. *A Quotient Space Hough Transform for Space-Variant Visual Attention.* **Submitted to Computer Vision, Graphics and Image Processing (1991). Alan Rojer and Eric L. Schwartz**

We consider the problem of "visual attention" in the context of space-variant machine vision: Is there a general theoretical and practical formulation for the "next-look" problem to guide a space-variant sensor to a rapid choice for its next fixation point? This topic is developed in the context of Hough transform methods, by the addition of a third space to the usual feature and object spaces considered in traditional Hough methods. This third space is a "behavioural," or "motor" space, which is typically low-dimensional with respect to the feature and object spaces. For example, the motor space of particular interest for us is the two-dimensional manifold of monocular eye positions. By "collapsing" the generalized Hough transform into a low dimensional motor space, we show that it is possible to avoid a practical difficulty in applying Hough transform methods, which is the exponential dependence of the accumulator array on the dimensionality of the object space. Beginning with a simple and very general Bayesian scheme, we derive in stages the generalized Hough transform as a special case. Since "attentional" applications, by their nature, require only partial knowledge about objects, computation of all the parameters characterizing a scene object is superfluous and wasteful of computational resources. This suggests that for an attentional application, collapsing the (large) object space onto the (small) motor space provides a computationally grounded definition of the term "visual attention". We illustrate these ideas with an example of choosing "fixation" points for a space variant sensor in a machine vision application for real-time reading of license plates of moving vehicles.

10. *A Bayesian Model for the Hough Transform.* **Submitted to Pattern Recognition (1991). Alan Rojer and Eric L. Schwartz.**

Although the Hough transform and its generalizations have been used for many years in computer vision and pattern recognition, its conceptual grounding has been largely heuristic. We demonstrate here that the generalized Hough transform may be viewed as a special case of Bayesian inference. Starting from a simple and very general Bayesian scheme, we derive in stages the generalized Hough transform(of Ballard). By doing so, we explicate a series of assumptions concerning featural independence and equal a priori occurrence of objects which are implicit in the use of the generalized Hough transform. When (if ever) these assumptions are satisfied, Hough transform methods are optimal (in a Bayesian sense) for object recognition. Consideration of the assumptions also illuminates conditions under which performance degradation of the Hough approach is expected. The goal of this paper is not to provide yet more variations on the Hough transform, but rather to clarify the implicit assumptions associated with this methodology, and to suggest future research in which these assumptions can verified or relaxed.

11. *Measurement, characterization and algorithmic synthesis of the macaque ocular dominance column pattern.* **Eric L. Schwartz and Alan Rojer. Invest. Opthal. and Vis. Sci. 31:1226 (1990).**

Columnar patterns in the visual cortex of cats and monkeys have usually been measured and described by qualitative techniques. The goal of this study was to develop quantitative descriptive methods for columnar patterns in visual cortex. In the present work, we show a quantitative measurement of the macaque ocular dominance column pattern, based on measurement of local power spectral densities of a computer reconstruction and numerical flattening of V1. The columnar pattern was observed following single eye enucleation and cytochrome oxidase staining. The parameters of an oriented spatial filter, characterized by a center frequency, a bandwidth, an orientation, and an aspect ratio, are sufficient to locally describe visual cortical columnar patterns. We present measurements that characterize the full ocular dominance column pattern of macaque V1 in this way. In addition, we demonstrate that this method is constructive as well as descriptive. By applying the measured filters to 2D white noise, followed by thresholding, high accuracy models of the original column patterns can be algorithmically constructed. In other words, the macaque ocular dominance column pattern is most simply described in terms of band-pass filtered white-noise. We show that a similar algorithm is capable of algorithmically reconstructing the cat (''patchy'') ocular dominance column pattern, as well as the orientation column patterns of cat and monkey. Moreover, we demonstrate that many of the previous algorithms that have been suggested to account for these data are essentially equivalent to our bandpass filtered white noise model. In summary, we present: 1.) The first fully quantitative measurement of the details of the macaque ocular dominance column pattern; 2.) A parametric technique for describing the range of columnar patterns found in cat and monkey visual cortex; 3.) An algorithm for synthesizing columnar patterns which is much faster than other method with which we are familiar, and which produces synthetic cortical patterns which are in detailed qualitative and quantitative agreement with the measured data.

No patent applications have been filed during this period.

Sincerely yours,

Eric Schwartz

Assoc. Prof. NYU Medical Center
Adj. Assoc. Prof. Computer Science, Courant Institute of Mathematical Sciences