Conte Center 2006 Report Summary

In the enclosed progress reports we describe the progress so far 36 months after the beginning of the project. As before, MIT continues to function as home site for the overall effort. Our Conte Center Web site at http://cbcl.mit.edu/cbcl/projects/nih-conte/index.html provides links to publications (see (http://cbcl.mit.edu/cbcl/projects/nih-conte/publications.htm) originating from our project, contains information about workshops (see http://cbcl.mit.edu/cbcl/projects/nih-conte/events.htm) organized by the Conte Center, and reports on our research, as well as information on the researchers involved in our effort (see http://cbcl.mit.edu/cbcl/projects/nihconte/investigators.htm). As always, feedback from NIH to improve the site and its usefulness to NIH would be highly appreciated!

1. Significance

Main Results. Despite enormous progress in the physiology and in the anatomy of visual cortex, the understanding of what it computes and of how it does it, remains fragmentary. The main outcome so far of this project is the realization that – quite surprisingly -- we may be on the verge of developing an initial quantitative theory of visual cortex, faithful to known physiology and able to mimic human performance in difficult recognition tasks, while outperforming current computer vision systems. The computational model of information processing in visual cortex is a quantitative summary of past data as well as of experiments done within the Center's sponsored projects. The scenario emerging from this combined physiological and computational approach is unexpectedly consistent, much more, so far, than we would have expected. The architecture summarizing the known anatomy and physiology of the ventral stream is consistent with V1, IT and PFC data, predicts properties of complex cells in V1 (Lampl *et al.*, 2004), of cells in V4 (see Pasupathy & Connor, 2001; Gallant *et al*., 1996; Freiwald *et al*., in preparation), predicts the level and the pattern of human performance in complex object recognition tasks. It also predicts (Kreiman, see Serre *et al*., 2005) quantitatively the range of invariance and amount of information represented at the level of IT and measured in a specific read-out experiment (Hung *et al.*, 2005). It asks a set of specific questions – from the number of objects than can be recognized at a glance to the role of feedback projections in a range of recognition tasks – which allow to plan a whole range of new experiments. A preliminary, detailed report on the computational work and on the associated experimental data is in T. Serre, M. Kouh, C. Cadieu, U. Knoblich, G. Kreiman and T. Poggio, A Theory of Object Recognition: Computations and Circuits in the Feedforward Path of the Ventral Stream in Primate Visual Cortex, *CBCL Paper #259/AI Memo #2005-036*, Massachusetts Institute of Technology, Cambridge, MA, October, 2005. We also started to do human fMRI recordings in humans, for which the model also appears to be a useful toll for the interpretation of the data and the planning of the experiments.

Collaborative Enterprise. Our team includes researchers in monkey physiology, human psychophysics and computational neuroscience. Our *Conte Center to Develop Collaborative Neuroscience Research* (using the P20 exploratory grant mechanism) is serving very well its function of developing collaborative arrangements while supporting a focused research project. The Center has created significant integration and synergy among members of the multidisciplinary research team and even with scientists involved in the activity of the Center through the advisory board (there are papers in preparation involving the Poggio and the Connors labs and also the Livingstone and Poggio labs). We have carried out mostly joint projects. In fact, most of the papers published with Conte support are joint papers among pairs of the groups involved. In addition, and perhaps more unique, is the role of the present Center in the demonstration that a theoretical and conceptual framework acts to unify a large body of disparate data from anatomy, physiology, psychophysics and computation, and thereby in permitting collaborations among researchers from these disparate areas (see papers at http://cbcl.mit.edu/cbcl/projects/nih-conte/publications.htm, such as Kreiman *et al.*, 2006; Hung *et al*., 2005; Quiroga, *et al*., 2005; Riesenhuber *et al*., 2004; Poggio *et al.*, 2004; Lampl *et al*., 2004; Freedman *et al.*, 2003). Thereby models interact with experiments and vice versa from day one and not just after the data are obtained.

Metagoal. The metagoal of this project is to demonstrate the usefulness of neurally plausible computational models in providing powerful new insights into the key problem of how the cortex works, how learning and intelligence arise from the dynamic interactions within and among cortico-thalamic circuits and how this is expressed at the behavioral level. We aim to show that computational models can be a powerful tool in integrating basic research across different levels of analysis from synaptic to cellular to systems to complex behavior. Our specific problem – how the ventral stream in visual cortex underlies object recognition -- is a perfect candidate for demonstrating the power of basic integrative research and to train a new generation of interdisciplinary researchers who span the computational, physical, biological, and behavioral sciences. The project thus represents basic research and training that will strengthen the scientific foundations of work on topics central to the public health mission of NIH, such as mental disorders.

In particular, understanding the structure and functioning of brain circuits underlying normal behavior is clearly critical for shedding light on underlying causes of behavioral abnormalities found in neural disorders and individual differences.
In our work we are emphasizing the marriage between computation and experiments. In fact, the distinguishing feature of our project is the strong collaboration between computational and experimental work in visual cortex. In terms of experimental techniques we have added brain imaging (fMRI) to intracellular and extracellular physiology and visual psychophysics.

We have made progress towards showing that quantitative models of complex neural system, when developed in close cooperation with experimental labs, can be tools to a) think about the problems (some cognitive problems are too complex for the qualitative, simple models used so far); b) make predictions, suggest and plan new experiments; c) analyze and interpret data; d) integrate experimental findings of different types and from different labs, drawing implications for future experiments from multiple sources of evidence.

2. Plans

We plan to hold a meeting of the Conte Center on September 11th and 12th, 2006, in the new Neuroscience building at MIT. The outside Board which reviewed our activities at our 2004 meeting has just agreed to meet again to evaluate our progress during the third year of the Conte Center. This advisory committee is composed of Drs. E. Connors (Johns Hopkins), L. Abbott (Columbia) and M. Livingstone (Harvard Medical). A preliminary agenda is available at our Web site under the URL http://www.ai.mit.edu/projects/cbcl/projects/nih-conte/Meeting_Agenda_2006.pdf.

In addition to the 30 or so researchers from the four Institutions directly involved in the project, other researchers from other institutions who are collaborating with us will participate and give brief talks (on the second day).

This will be the fifth comprehensive meeting of our group since we started putting the proposal together, and the third official one as a Conte Center and with an external advisory committee. The main function of the meeting will be to further communication and interactions among our groups from MIT, CalTech, Northwestern and Georgetown and our external collaborators.

3. Report from the Center's External Advisory Board

The advisory board met on August 29th, 2005, at the Academy of Arts and Sciences, Cambridge after our annual workshop/review of the NIH-funded Conte Project on "Detection and Recognition of Objects in the Visual Cortex" (see http://cbcl.mit.edu/cbcl/projects/nih-conte/index.html also for agenda and talks abstracts). The letter of the board -- composed by Marge Livingston (Harvard Medical), Larry Abbot (Brandeis), and Charles Connor (Johns Hopkins) – evaluates the first two years of our Center and is enclosed below.

LETTER OF THE ADVISORY BOARD (Tuesday, 20 September 2005)

Dear Tommy,

The advisory board for the Conte Center met on August 29, 2005 with all the PIs of the grant and many of their students and postdocs. The progress in each module of the grant was presented, with a great deal of discussion. At the end of the day the advisory board met with the PIs jointly. Below is a summary of the advisory board's impressions:

Progress has been substantial and impressive. It has turned out that the HMAX computational model for object recognition is an effective way to organize many kinds of approaches at many different levels, both physiological and computational, and this has suggested several lines of physiological experiments that have been initiated. Furthermore the physiological results have in turn suggested modifications that have been incorporated into the model. The advisory board had no substantial concerns, except for the continued under-representation of women in the project, and was again very enthusiastic about the progress and future directions.

A very positive aspect of the center is that, while the HMAX model has guided experiments, it has also been modified and improved in response to experimental results and other considerations. Some of the physiological studies (see DiCarlo's lab below) suggest that cells may perform an averaging computation, rather than a MAX-like operation, and the model can show such properties under certain conditions as a result of all the previous layers in the model. The physiological data were useful in indicating modifications of the model, and now the HMAX model (Poggio) has been modified l so that it uses a more conventional "dot product" approach to approximate the Gaussian tuning curves of the original model. In fact, results suggest that the same circuit, implemented in a biophysically reasonable manner utilizing shunting inhibition, can produce both Gaussian tuning properties and a MAX-like operation. These changes have let to reciprocal interactions between the model and the physiology in V1, V4, inferotemporal cortex, and prefrontal cortex, and between the model and the psychophysics of face and object recognition. Predictions of this aspect of the model are currently being tested in the laboratories of Riesenhuber, Miller, Connor, and Livingstone. In the future, the evolving HMAX model should continue to provide the basic framework for close coordination between modeling, neurophysiology, functional imaging, and psychophysics. The model has now incorporated a new learning rule which has drastically improved the recognition performance of the model in clutter and can result in ultra-rapid object categorization using feed-forward circuitry. Predictions from this model about identification behavior of IT neurons are currently being tested by Millers lab; predictions about neural categorization behavior are being tested in DiCarlo's lab; and predictions about behavioral ultra-rapid object categorization are being tested in Koch's lab.

Riesenhuber recently moved his lab to Georgetown University, so his lab now constitutes a new module. Their studies have tested the psychophysical predictions of the model for human object recognition in visual clutter. They have used both fMRI and human psychophysics to test the ability of humans to discriminate faces along a morphed continuum. The model predicts asymptotic behavior for larger differences between faces, and both perceptual and fMRI adaptation experiments reveal such behavior.

Ferster's laboratory has used intracellular recordings of cells in cat V1 to test the principle of the MAX operation in V1 complex cells. This is an important test of a fundamental tenet of the model. The first results from this study have been published. They show that the MAX operation is a valid characterization of the nonlinear stimulus integration performed by complex cells. Further studies have revealed two populations of V1 complex cells, those that perform a MAX-like operation, and those that show substantial interactions between regions of the receptive field, as originally reported by Movshon *et al*. They now propose to explore other physiological properties that may distinguish the two populations of cells, and to look for circuit mechanisms underlying the two behaviors.

DiCarlo's laboratory has made further progress in testing predictions of the HMAX model on the tolerance of IT neural responses to clutter (multiple objects of varying similarity within the receptive field). Results indicate that IT neurons respond to multiple objects within their receptive fields at a level approximating the average of the responses to the two separate objects, rather than the maximum of the two. These physiological studies have suggested modifications of the MAX model, which are being incorporated by Poggio’s group (see above).

Miller's laboratory has been comparing the behavior of the top-level units in the model to the responses of IT cells during a learned object categorization task. Consistent with the model, some IT cells are more sensitive to object shape characteristics than to category membership, and some the reverse. In the future, new manipulations of object category learning tasks and greater stimulus variation with respect to learned category boundaries should lead to even more productive model/neurophysiology interactions.

Koch's laboratory has been testing the predictions of the model on human psychophysics of face recognition and object recognition with and without attentional load. Recent studies have shown that humans can make categorical judgments about natural stimuli without using attention. Novel studies on alert human subjects with chronic electrodes implanted for epilepsy have shown neural correlates of change detection and change blindness. Studies of eye movements during visual search are being explored to ask how features are used to guide visual search.

In summary, the advisory board was impressed with both the level of scientific achievement and the level of cooperative interaction among the sub-groups of the MIT Conte Center. We plan to continue to advise the group as it looks forward to expanding the Center.

<u>The Advisory Board (Livingstone, Abbot, Connors)</u>