FINAL TECHNICAL REPORT

A MURI Center for Intelligent Biomimetic Image Processing and Classification

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Scientific and Technical Objectives

This MURI project develops a SMartVISION general-purpose, autonomous neural system for vision, object recognition, and tracking applications, to explain how the brain sees, and to transfer new computer vision architectures into technology. SMartVISION predictions have been successfully tested in psychophysics and neurobiology labs. SMartVISION embodies a revolutionary paradigm shift in intelligent computation. It is designed to operate in real-time within noisy environments for which rules are not known, and which contain rare but important events, unexpected events, incomplete data, irregular statistical drifts, and different amounts of morphological variability in objects to be detected and recognized. A companion architecture for distributed planning, decision, and action helps to actively acquire information by interacting with the SMartVISION system, including circuits to control attention shifts and eye movements to fixate regions of interest. SMartVISION is quantitatively simulating the dynamics of identified nerve cells, in known anatomical circuits, and the emergent behaviors that they control. It embodies qualitatively new computational paradigms with novel concepts and mechanisms for intelligent computing in response to a rapidly changing world, notably the paradigms of Laminar Computing and of Complementary Computing. These concepts and mechanisms have begun to break through old barriers in technology.

Approach

Senior faculty coordinate small teams of faculty/student researchers on projects to develop the unified SMartVISION system. Biological modeling projects discover fundamental organizational principles and mechanisms that enable the brain to adapt in real-time to unexpected environmental challenges, translate them into mathematical models, and use the models to quantitatively simulate large brain and behavioral data bases about vision, object recognition, and tracking. These models have introduced two revolutionary new paradigms into intelligent computing, Laminar Computing and Complementary Computing, whose impact will be increasingly felt during the next several decades. A linkage between brain and behavior is necessary for technology transfer, because brain mechanisms say how it works, and behavioral functions say what it is for. Moreover, models that can adapt autonomously in real time to a changing world are of great importance in solving outstanding technological problems. That is why, on the technological side, brain/behavior models from BU have been used and further developed by a number of companies, hospitals, and national labs to process data from artificial sensors such as synthetic aperture radar, laser radar, multispectral infrared, night vision, nuclear magnetic resonance, and high altitude photography for large-scale applications to DoD applications and technology.

Concise Accomplishments

Biological projects include laminar cortical and subcortical models of: (1) 3D vision and figure-ground separation in response to natural scenes and psychophysical displays; (2) 3D form-motion interactions to generate representations of object direction and speed; (3) 3D shape-from-texture; (4) learning and recognition of object textures using surface-based spatial attention and object attention; (5) learning view-invariant 3D object categories from multiple 2D view categories using active eye movements, surface-based spatial attention, and object attention; (6) learning to recognize natural scenes using multiple-scale filters and form-fitting spatial attention; (7) temporary storage of event sequences in working memory, learning of sequential plans, and sequence performance during cognitive information processing; (8) coordinated ballistic and smooth pursuit predictive movements that maximize visual acuity; (9) navigation and obstacle avoidance using optic flow while eyes/cameras scan the environment; (10) applications of biological models of normal cognition to understand autism. Technological projects include: (1) an image processing system to generate visible chromatic and achromatic scenes under variation illumination conditions; (2) information fusion by unsupervised discovery of rules and hierarchical knowledge from multi-faceted data; (3) image analysis by long-range object completion and figure-ground segmentation to locate watersheds, fault lines, and roads; (4) a color vision model that directs attention to small objects in complex scenes; (5) a testbed to predict HIV resistance to antiretroviral therapy; (6) a technology website and image analysis and classification toolkits; (7) 3D VLSI CMOS implementation of neocortical processing; (8) silicon neurons and photoreceptors in 3D CMOS technology; (9) wireless architecture for cortical distributed processing.

Expanded Accomplishments

Selected accomplishments are summarized here:

View-invariant object learning and recognition: Often objects can be recognized from different viewpoints. How can the brain, or a computer vision system, accomplish autonomous learning and recognition of an object from multiple viewpoints while scanning a scene with eye movements? How does the brain avoid the problem of erroneously classifying parts of different objects together? How are attention and eye movements intelligently coordinated to facilitate object learning? A neural model provides a unified mechanistic explanation of how spatial and object attention work together to search a scene and learn what is in it. The ARTSCAN model of Fazl, Grossberg, and Mingolla predicts how an object's surface representation generates a form-fitting distribution of spatial attention, or "attentional shroud." All surface representations dynamically compete for spatial attention to form a shroud. The winning shroud persists during active scanning of the object. The shroud maintains sustained activity of an emerging view-invariant category representation while multiple view-specific category representations are learned and are linked through associative learning to the view-invariant object category. The shroud also helps to restrict scanning eye movements to salient features on the attended object. Object attention plays a role in controlling and stabilizing the learning of view-specific object categories. Spatial attention hereby coordinates the deployment of object attention during object category learning. Shroud collapse releases a reset signal that inhibits the active view-invariant category in the What cortical processing stream. Then a new shroud, corresponding to a different object, forms in the Where cortical processing stream, and search using attention shifts and eye movements continues to learn new objects throughout a scene. The model mechanistically clarifies basic properties of attention shifts (engage, move, disengage) and inhibition of return. It simulates human reaction time data about object-based spatial attention shifts, and learns with 98.1% accuracy and a compression of 430 on a letter database whose letters vary in size, position, and orientation.

Texture segregation by visual cortex: A neural model called dARTEX was developed by Bhatt, Carpenter, and Grossberg to demonstrate how laminar interactions in the visual cortex may learn and recognize object texture and form boundaries. The model unifies five interacting processes: region-based texture classification, contour-based boundary grouping, surface filling-in, spatial attention, and object attention. The model shows how form boundaries can determine regions in which surface filling-in occurs; how surface filling-in interacts with spatial attention to generate a form-fitting distribution of spatial attention, or attentional shroud; how the strongest shroud can inhibit weaker shrouds; and how the winning shroud regulates learning of texture categories, and thus the allocation of object attention. The model can discriminate abutted textures with blurred boundaries and is sensitive to texture boundary attributes like discontinuities in orientation and texture flow curvature as well as to relative orientations of texture elements. The model quantitatively fits the Ben-Shahar and Zucker (2004) human psychophysical data on orientation-based textures. Surface-based attentional shrouds improve texture learning and classification: Brodatz texture classification rate varies from 95.1% to 98.6% with correct attention, and from 74.1% to 75.5% without attention. Object boundary output of the model in response to photographic images was favorably compared to computer vision algorithms and human segmentations.

Scene understanding: This project addresses the problem of how humans rapidly recognize a scene. It clarifies how neural models can capture this biological competence to achieve state-of-the-art scene classification. The ARTSCENE model of Grossberg and Huang classifies natural scene photographs by using multiple spatial scales to efficiently accumulate evidence for gist and texture. ARTSCENE embodies a coarse-to-fine Texture Size Ranking Principle whereby spatial attention processes multiple scales of scenic information, ranging from global gist to local properties of textures. The model can incrementally learn and predict scene identity by gist information alone and can improve performance through selective attention to scenic textures of progressively smaller size. ARTSCENE discriminates 4 landscape scene categories (coast, forest, mountain and countryside) with up to 91.58% correct on a test set, outperforms alternative models in the literature which use biologically implausible computations, and outperforms component systems that use either gist or texture information alone. Model simulations also show that adjacent textures form higher-order features that are also informative for scene recognition.

Thus, ARTSCENE is part of a larger research program, illustrated as well by the above three projects, for clarifying how processes of multiple-scale texture filtering and grouping, spatial attention, fast category learning and recognition, and scanning eye movements can work together to achieve impressive visually-based learning and recognition competences.

3D shape-from-texture: In addition to its value in the recognition of natural objects, texture information may be used to generate representations of object shape that cannot be easily explained using more traditional 3D modeling approaches. To complement the analysis of how multiple-scale filters are used for texture recognition, a LIGHTSHAFT (LIGHTness-and-SHApe-From-Texture) neural model was developed by Grossberg, Kuhlmann, and Mingolla to clarify how cortical areas V1, V2, and V4 interact to convert a textured 2D image into a representation of curved 3D shape. Two basic problems were solved to achieve this: (1) Patterns of spatially discrete 2D texture elements were transformed into a spatially smooth surface representation of 3D shape. (2) Changes in the statistical properties of texture elements across space induced the perceived 3D shape of this surface representation. This is achieved in the model through multiple-scale filtering of a 2D image, followed by a cooperative-competitive grouping network that coherently binds texture elements into boundary webs at the appropriate depths using a scale-to-depth map and a subsequent depth competition stage. These boundary webs then gate filling-in of surface lightness signals in order to form a smooth 3D surface percept. The model quantitatively simulates challenging psychophysical data about perception of prolate ellipsoids (Todd and Akerstrom, 1987, *J. Exp. Psych.*, **13**, 242). In particular, the model represents a high degree of 3D curvature for a certain class of images, all of whose texture elements have the same degree of optical compression, in accordance with percepts of human observers. Simulations of 3D percepts of an elliptical cylinder, a slanted plane, and a photo of a golf ball are also presented.

Information fusion: Unsupervised discovery of rules and hierarchical knowledge from multi-faceted data: Carpenter, Amis, Ogas, and Olivera developed new methods that build upon a novel approach, which was introduced in a prior MURI project, to the information fusion problem. These methods derive consistent knowledge from sources that are paradoxically both inconsistent and accurate. A new ARTMAP neural network system derives hierarchical knowledge structures from nominally inconsistent training data. The system learns, for example, that disparate pixels map to the output class "beach"; but, if similar or identical pixels are, at other times, labeled "plage" or "open space" or "natural", the system learns to associate multiple classes with a given input. Testbed image examples have shown that the overall pattern of distributed predictions can reveal a knowledge hierarchy which guides the production of consistently layered maps of test regions. Even though no inter-class relationships are specified during training, the system uses distributed activation patterns of learned codes to derive knowledge of relationship rules, confidence estimates, equivalence classes, and hierarchical structures.

Image analysis: Long-range object completion and figure-ground segmentation: The CONFIGR (CONtour FIgure GRound) model of Carpenter, Mingolla, and Gaddam is a computational model based on principles of biological vision that completes sparse and noisy image figures. Within an integrated vision/recognition system, CONFIGR posits an initial recognition stage which identifies figure pixels from spatially local input information. The resulting, and typically incomplete, figure is fed back to the "early vision" stage for long-range completion via filling-in. The reconstructed image is then re-presented to the recognition system for global functions such as object recognition. In the CONFIGR algorithm, the smallest independent image unit is the visible pixel, whose size defines a computational spatial scale. Once pixel size is fixed, the entire algorithm is fully determined, with no additional parameter choices. Multi-scale simulations illustrate the vision/recognition system. Open-source CONFIGR code is available online, but all examples can be derived analytically, and the design principles applied at each step are transparent. The model balances filling-in as figure against complementary filling-in as ground, which blocks spurious figure completions. Lobe computations occur on a subpixel spatial scale. Originally designed to fill-in missing contours in an incomplete image such as a dashed line, the same CONFIGR system connects and segments sparse dots, and unifies occluded objects from pieces locally identified as figure in the initial recognition stage. The model self-scales its completion distances, filling-in across gaps of any length, where unimpeded, while limiting connections among dense image-figure pixel groups that already have intrinsic form. Long-range image completion promises to play an important role in adaptive processors that reconstruct images from highly compressed video and still camera images.

Laminar cortical dynamics of Cognitive and motor working memory, sequence learning and performance: After the brain perceives and recognizes individual objects and events, it needs to organize them into sequential plans in order to generate situationally-appropriate actions. In order to do this, it needs to store sequences of events temporarily in a working memory. How does the brain carry out working memory storage, categorization, and voluntary performance of event sequences? The LIST

PARSE neural model was developed by Grossberg and Pearson to propose an answer to this question that unifies the explanation of cognitive, neurophysiological, and anatomical data from humans and monkeys. It quantitatively simulates human cognitive data about immediate serial recall and free recall, and monkey neurophysiological data from the prefrontal cortex obtained during sequential sensory-motor imitation and planned performance. The model clarifies why both spatial and non-spatial working memories share the same type of circuit design. It proposes how the laminar circuits of lateral prefrontal cortex carry out working memory storage of event sequences within layers 6 and 4, how these event sequences are unitized through learning into list chunks within layer 2/3, and how these stored sequences can be recalled at variable rates that are under volitional control by the basal ganglia. These laminar prefrontal circuits are variations of laminar circuits in the visual cortex that have been used to explain data about how the brain sees. These examples from visual and prefrontal cortex illustrate how laminar neocortex can represent both spatial and temporal information, and open the way towards understanding how other behaviors may be represented and controlled by variations on a shared laminar neocortical design. When enough examples of such laminar computing are developed, they will open the way towards designing families of VLSI chips, all variations of a shared laminar cortical design, that can be self-consistently integrated into an autonomous controller of multiple modalities of intelligence.

Coordinating saccadic and smooth pursuit eye movements during visual tracking of unpredictably moving targets: As illustrated by the above projects on visual learning and recognition, oculomotor tracking of moving objects is an important component of visually based cognition, planning, and decision-making. The ARTSCAN and model, in particular, demonstrates how eye movements may be used to learn view-invariant object categories, but it does not explain how the brain generates these eye movements. The brain has a fovea with high visual acuity that must be moved efficiently across a scene to see and understand it well. Ballistic or saccadic eye movements, by themselves, would greatly diminish the amount of time that the fovea fixates objects of interest. The brain intelligently coordinates saccades with predictive smooth pursuit movements to maximize the amount of time that a moving target is foveated. In particular, the saccadic and smooth pursuit systems interact to often choose the same target, and to maximize its visibility through time. How does the brain coordinate these two types of eye movements to track objects that move in unpredictable directions and speeds? How do multiple brain regions interact, including frontal cortical areas, to decide the choice of a target among several competing moving stimuli? How can these insights be used to develop more effective machine tracking methods: Saccadic eye movements rapidly foveate peripheral visual or auditory targets, and smooth pursuit eye movements keep the fovea pointed toward an attended moving target. Analyses of tracking data in monkeys and humans reveal systematic deviations from predictions of the simplest model of saccade-pursuit interactions, which would use no interactions other than common target selection and recruitment of shared motoneurons. Instead, saccadic and smooth pursuit movements cooperate to cancel errors of gaze position and velocity, and thus to maximize target visibility through time. Moreover, saccades are calibrated to correctly foveate a target despite its continued motion during the saccade?

A neural model has been developed by Bullock, Grossberg, and Srihasam to provide answers to such questions. The modeled interactions encompass motion processing areas MT, MST, FPA, DLPN and NRTP; saccade planning and execution areas FEF and SC; the saccadic generator in the brain stem; and the cerebellum. Simulations illustrate the model's ability to functionally explain and quantitatively simulate anatomical, neurophysiological and behavioral data about saccade-pursuit target tracking.

Visually-guided steering, obstacle avoidance, and route selection: Tracking of moving targets often occurs while a human, or mobile robot, navigates an environment. How is optic flow information used to steer towards a goal while avoiding obstacles? A Steering, Tracking, And Route Selection (STARS) neural model was developed by Elder, Grossberg, and Mingolla to explain how humans can approach a goal object on foot while steering around obstacles to avoid collisions in a cluttered environment. The model uses optic flow from a 3D virtual reality environment to determine the position of objects based on motion discontinuities, and computes heading direction, or the direction of self-motion, from global optic flow. The cortical representation of heading interacts with the representations of a goal and obstacles in such a way that the goal acts as an attractor of heading, while obstacles act as repellers. This result clarifies behavioral data that demonstrate such an attractor/repeller scheme. In addition, the model maintains fixation on the goal object by generating smooth pursuit eye movements, whose finer control is clarified by the model of Bullock, Grossberg, and Srihasam. Eye rotations can distort the optic flow field, complicating heading perception, and the model uses extraretinal signals to correct for this distortion and accurately represent heading. The model explains how motion processing mechanisms in cortical areas MT, MST, and VIP can be used to guide steering. The model quantitatively simulates human psychophysical data about visually-guided steering, obstacle avoidance, and route selection. The model architecture captures the attractor/repeller dynamics of steering behavior, and clarifies how heading and eye movements work together during complex steering tasks.

A modular architecture for implementing cortical processing through forward, feedback, and lateral connections: A CMOS cortical processor chip has been fabricated in MIT Lincoln Labs 3D 0.18 um CMOS technology for a 64 x 64 processor that incorporates 1 million transistors in 1.5 x 1.5 mm of silicon. 10 3D CMOS dies were received in May 2006. A printed circuit board has been designed to test the chips. Preliminary results are encouraging.

CUMULATIVE LIST OF PUBLICATIONS
May 1, 2001 – August 31, 2007

Peer-Reviewed Publications

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100. Polimeni, J., Balasubramanian, M., and Schwartz, E.L. (2003). Full-field two-dimensional V1, V2, and V3 visuotopy represented by a quasiconformal map complex. In *Abstracts of the Society for Neuroscience (SFN)*, November.

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105. Shock, B.M., Carpenter, G.A., Gopal, S., and Woodcock, C.E. (2001). ARTMAP neural network classification of land use change. Technical Report CAS/CNS TR-2001-009, Boston University. In **Proceedings of the world congress on computers in agriculture and natural resources**, Iguaça Falls, Brazil, September.

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108. Srihasam, K., Bullock, D., and Grossberg, S. (2006). Interactions of saccadic and smooth pursuit eye movements for effective visual tracking and perception of objects moving at variable speeds. In **Proceedings of the 10th international conference on cognitive and neural systems (ICCNS)**, Boston University, p.117.

109. Srihasam, K., Bullock, D., and Grossberg, S. (2007). Target selection in a neural model for coordination of saccades and smooth pursuit. In **Proceedings of the 11th international conference on cognitive and neural systems (ICCNS)**, Boston MA, May p.36.

110. Srihasam, K., Bullock, D., and Grossberg, S. (2007). Coordination of saccadic and smooth pursuit eye movements during target selection and

tracking. In *Abstracts of the Society for Neuroscience (SFN)*, San Diego CA, November.

111. Srinivasa, N. and Grossberg, S. (2007). A head-neck-eye camera system that learns to saccade to 3-D targets via action-perception cycles. In **Proceedings of the 11th international conference on cognitive and neural systems (ICCNS)**, Boston MA, May, p.64.

112. Srinivasa, N. and Grossberg, S. (2007). A self-organizing neural model for fault-tolerant control of redundant robots. In **Proceedings of the 20th international joint conference on neural networks (IJCNN)**, Orlando FL, August.

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115. Tan, A.-H., Carpenter, G.A., and Grossberg, S. (2007). Intelligence through interaction: Towards a unified theory for learning. In **Proceedings of the fourth international symposium on neural networks** [abstract #2-09-0148], Nanjing, China, June.

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117. Versace, M. and Grossberg, S. (2005). Temporal binding and resonance in thalamocortical assemblies: Learning and cognitive information processing in a spiking neuron model. In *Abstracts of the Society for Neuroscience (SFN)*, Washington DC, November.

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119. Versace, M. and Grossberg, S. (2006). From spikes to objects: How multiple levels of thalamic and cortical interactions control visual learning, attention, and recognition. In *Abstracts of the Vision Sciences Society (VSS)*, Sarasota FL, May.

120. Versace, M. and Grossberg, S. (2006). Learning and cognitive information processing in thalamocortical assemblies: Unifying spikes, synchronous oscillations, and resonance. In **Proceedings of the 10th international conference on cognitive and neural systems (ICCNS)**, Boston University, p.71.

121. Versace, M. and Grossberg, S. (2007). Spikes, synchrony, and attentive learning by laminar thalamocortical circuits. In **Proceedings of the conference on Coherent behavior in neuronal neural networks (CoBeNN)**, Mallorca, Spain, October.

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125. Yazdanbakhsh, A. and Grossberg, S. (2003). A laminar cortical model of 3-D surface stratification, transparency, and neon color spreading. In **Proceedings of the 7th international conference on cognitive and neural systems (ICCNS)**, Boston University, May, p.9.

126. Yazdanbakhsh, A. and Grossberg, S. (2003). How does perceptual grouping in the cortex synchronize quickly? In **Proceedings of the 7th international conference on cognitive and neural systems (ICCNS)**, Boston University, May, p.15.

127. Yazdanbakhsh, A. and Grossberg, S. (2005). A laminar cortical model of binocular rivalry. In **Proceedings of the 9th international conference on cognitive and neural systems (ICCNS)**, Boston University, May, p.10.

128. Yazdanbakhsh, A. and Grossberg, S. (2005). What cortical mechanisms of 3D vision cause binocular rivalry? In *Abstracts of the Society for Neuroscience (SFN)*, Washington DC, November.

129. Zhang, Z. and Andreou, A.G. (2007). Design of an ultra wideband transmitter in 0.18um 3D silicon on insulator CMOS. In **Proceedings of the 41st annual conference on information sciences and systems (CISS07)**, Baltimore MD, March, pp.750-753.

HONORS AND AWARDS

1. Andreou, A., Graduate student Julio Georgiou received a travel fellowship award to attend the Ninth International Conference on Cognitive and Neural Systems (ICCNS), Boston, May 2005.
2. Bullock, D., Editorial board member of the journal *Neural Networks*.
3. Carpenter, G.A., Founding member of the International Neural Network Society (INNS) Governing Board (1987–present).
4. Carpenter, G.A., Editorial board member of the journals *Brain Research* (Cognitive Brain Research Section), *IEEE Transactions on Neural Networks*, *International Journal of Hybrid Intelligent Systems* (Regional Editor), *Neural Computation*, *Neural Networks*, *Neural Processing Letters*.
5. Carpenter, G.A., Accreditation Board for *Computer Abstracts*.
6. Carpenter, G.A., Program Committee member for the International Joint Conference on Neural Networks (IJCNN), Washington DC, July 2001.
7. Carpenter, G.A., Program Committee member for the International Joint Conference on Neural Networks (IJCNN), Honolulu HI, May 2002.
8. Carpenter, G.A., Program Committee member for the Euro-International Symposium on Computational Intelligence (ISCI), Kosice, Slovakia, June 2002.
9. Carpenter, G.A., Award from the Slovak Artificial Intelligence Society, 2002.
10. Carpenter, G.A., Program Committee member for the International Joint Conference on Neural Networks (IJCNN), Montreal, Canada, July 2005.
11. Carpenter, G.A., Member of the 2005 AMS-AAAS Liaison Committee of the American Mathematical Society (AMS) (appointed to 2-year term by AMS President).
12. Carpenter, G.A., Recipient of the IEEE Neural Networks Pioneer Award, 2008.
13. Carpenter, G.A. and Grossberg, S., Exclusive worldwide license for five patents sold by Boston University to Intellectual Ventures, LLC in November 2005. Upfront fee $200,000 plus 10% of any profits received from sublicensing income:
    - Carpenter, G.A. & Grossberg, S., U.S. Patent No. 5,142,590: Pattern recognition system (Filed: November 27, 1985. Issued: August 25, 1992. European Patent No. 0244483, issued July 15, 1992). (ART 1).
    - Carpenter, G.A. & Grossberg, S., U.S. Patent Nos. 4,914,708 and 5,133,021: System for self organization of stable category recognition codes for analog patterns (Filed: June 19, 1987. Issued: April 3, 1990 and July 21, 1992). (ART 2).
    - Carpenter, G.A. & Grossberg, S., U.S. Patent No. 5,311,601: Pattern recognition system with variable selection weights (Filed: January 12, 1990. Issued: May 10, 1994). (ART 3).
    - Carpenter, G.A., Grossberg, S., & Rosen, D.B., U.S. Patent No.

5,157,738: Rapid category learning and recognition system (Filed: December 19, 1990. Issued: October 20, 1992). (ART 2 A).

- Carpenter, G.A., Grossberg, S., & Reynolds, J.H., U.S. Patent No. 5,214,715: Predictive self organizing neural network. (Filed: January 31, 1991. Issued: May 25, 1993). (ARTMAP).

14. Grossberg, S., Founding member of the International Neural Network Society (INNS) Governing Board (1987–present).
15. Grossberg, S., Founding Editor-in-Chief of *Neural Networks*, the official journal of the International Neural Network Society (INNS), the European Neural Network Society (ENNS), and the Japanese Neural Network Society (JNNS). Re-elected by INNS Board of Governors for each five-year term, 1987–present.
16. Grossberg, S., Listed in Highly Cited Researchers database by the ISI Web of Science (less than 1/2 % of all published researchers).
17. Grossberg, S., Editor of the journals *Adaptive Behavior*; *Applied Intelligence*; *Behavioral and Brain Sciences* (Associate Editor for Computational Neuroscience); *Behavioural Processes*; *Cognition and Brain Theory*; *Cognitive Brain Research*; *Cognitive Processing*; *Cognitive Science*; *IEEE Expert*; *IEEE Transactions on Neural Networks*; *Information Science*; *International Journal of Cognitive Science*; *International Journal of Uncertainty, Fuzziness, and Knowledge-Based Systems*; *Journal of Cognitive Neuroscience*; *Journal of Mathematical Psychology*; *Journal of Theoretical Neurobiology*; *Mathematical Biosciences*; *Mind and Society*; *Neural Computation*; *Nonlinear Analysis*.
18. Grossberg, S., General Chairman and Organizer, Fifth International Conference on Cognitive and Neural Systems (ICCNS), Boston University, May 2001.
19. Grossberg, S., Honorary Chairman, International Conference on Computational Intelligence for Modeling, Control, and Automation, Las Vegas NV, July 2001.
20. Grossberg, S., Organizing Committee member, annual Artificial Neural Networks in Engineering (ANNIE) conference, St. Louis MO, November 2001.
21. Grossberg, S., International Advisory Board, *Mind and Society* (new journal), February 2002.
22. Grossberg, S., Advisory Board, **Advanced Information Processing**, new book series, Springer-Verlag (Computer Science), February 2002.
23. Grossberg, S., Editorial Board, *Mathematical Modeling: Theory and Applications* (monographs), Kluwer, February 2002.
24. Grossberg, S., Charles River Award, Behavioral Toxicology Society, April 2002.
25. Grossberg, S., IEEE Senior Member, May 2002.
26. Grossberg, S., General Chairman and Organizer, Sixth International Conference on Cognitive and Neural Systems (ICCNS), Boston University, May 2002.
27. Grossberg, S., Fellow, American Psychological Society (APS), June 2002.
28. Grossberg, S., International Program Committee for the second Euro-International Symposium on Computational Intelligence (ISCI), Kosice, Slovakia, June 2002.
29. Grossberg, S., Program Committee member, International Conference on Information Processing and Management of Uncertainty in Knowledge-Based Systems, Annecy, France, 2002.

30. Grossberg, S., Advisory Committee for IEEE International Conference on Industrial Technology (also invited to be Keynote Speaker; declined), Bangkok, Thailand, 2002.
31. Grossberg, S., Honorary Program Committee member, Seventh Brazilian Symposium on Artificial Neural Networks, 2002.
32. Grossberg, S., International Advisory Board, **Encyclopedia of Consciousness and Subjectivity: Phenomenology, Cognitive Neuroscience, and Psychiatry,** Kluwer Press, 2002.
33. Grossberg, S., Editor of a new journal on *Current Opinion in Cognitive Neurodynamics*, 2005.
34. Grossberg, S., Editor of the new *International Journal of Humanoid Robotics*, 2005.
35. Grossberg, S., Editor of the new *International Journal of Hybrid Intelligent Systems*, 2005.
36. Grossberg, S., One of five founding editors of *Brains, Minds & Media*, a new e-journal devoted to educational technology and teaching in the neural and cognitive sciences, 2005.
37. Grossberg, S., Editorial board member of the journal *Advanced Information and Knowledge Processing*, 2005.
38. Grossberg, S., Competitively chosen two-hour tutorial with Ennio Mingolla entitled "How the Brain Sees" at the first-ever annual Vision Sciences Society (VSS) Satellite Workshop, May 2005. This was the only modeling presentation selected.
39. Grossberg, S., General Chairman of the Ninth International Conference on Cognitive and Neural Systems (ICCNS), Boston University, May 2005.
40. Grossberg, S.: Program Committee member for the conference on Information Processing and Management of Uncertainty in Knowledge-Based Systems, 2005.
41. Grossberg, S., Invited to be an editor of the *International Journal of Neural Systems*, July 2005.
42. Grossberg, S., Honored at a two-day meeting "An Anniversary Conference Celebrating Steve Grossberg@65 and CNS@15", Boston University, September 2005 (http://www.cns.bu.edu/events/Sept2005conference/index.html).
43. Grossberg, S., Invited to be an editor of the journal *Cognitive Neurodynamics*, February 2006.
44. Grossberg, S., Elected IEEE Fellow, November 2005.
45. Mingolla, E., Editorial board member of the journals *Neural Networks* and *Ecological Psychology*.
46. Mingolla, E., Guest Editor of the journal *Spatial Vision*, Volume 18, No. 2, 2005.
47. Mingolla, E., Competitively chosen two-hour tutorial with Stephen Grossberg entitled "How the Brain Sees" at the first-ever annual Vision Sciences Society (VSS) Satellite Workshop, May 2005. This was the only modeling presentation selected.
48. Mingolla, E., Helmholtz Award, International Neural Network Society (INNS), 2007.
49. Schwartz, E., Editorial board member of the journal *Neural Networks*.

Patent Activity

No patents were submitted or issued during the award period.

Technology Transfer

HRL Laboratories: HRL (formerly Hughes Research Laboratories) is now owned by Boeing, GM, and Raytheon. Professors Carpenter, Grossberg, and Mingolla worked with HRL researchers to develop a large-scale system to control an autonomous intelligent agent. DARPA funds, from the BICA (Biologically Inspired Cognitive Architectures) program, have been funding this collaborative relationship; see http://www.hrl.com/html/prsRls_060501.htm. Many of these designs grew out of ONR MURI funding. CNS faculty have consulted with HRL scientists, but this limited relationship played a key role in getting HRL a Phase I award. CNS will work with HRL to try to get a Phase II BICA grant.

Nanyang Technological University: Faculty, notably Professors Ah-Hwee Tan and Alex Tay, at this University have made plans to incorporate CNS algorithms into adaptive autonomous mobile robots for industry. Professor Tay visited CNS in 2005 and Professor Tan visited in 2006 to discuss possible approaches with Professors Carpenter and Grossberg. A colleague of Professors Tan and Tay, Dr. Gee Wah Ng, Head of the Advanced Analysis and Fusion Laboratory of the DSO National Laboratories in Singapore, visited CNS on sabbatical in 2006-2007 to continue this collaboration.

Intellectual Ventures, LLC (http://www.intellectualventures.com/): Sale by Boston University of five ART patents (November, 2005). Exclusive worldwide license sold by Boston University to Intellectual Ventures, LLC. See the Honors and Awards section of this report for further details.

MIT Lincoln Laboratory: MURI vision, recognition, and control neural algorithms have been transferred to MIT Lincoln Laboratory for use in cutting-edge DoD applications, and transferred from there to other DoD labs. More than 10 CNS PhDs were hired by Lincoln to facilitate technology transfer. That cooperation ended when its leader left Lincoln to work on national security issues in a company. It is now being rekindled by one CNS PhD, Dr. William Ross, who was hired by Lincoln Lab. Ross, now a Lincoln assistant group leader, has arranged for an employee to get Lincoln funding to earn an MA degree at CNS and to do collaborative research between CNS and Lincoln Lab. More cooperation is anticipated in the future.

Technology Website: The CNS Technology Lab under Professor Carpenter's direction has developed a website (http://cns.bu.edu/techlab) to present open source code, challenge problems, recent image processing and adaptive pattern recognition and prediction algorithms for technology, data sets, user-friendly biological neural models, benchmark studies, tutorials, and current research articles for use by the world-wide technology community. This resource will create many new technology transfer opportunities and applications. Many companies have used CNS image-processing and pattern recognition algorithms in their products. The website will expedite commercialization by making documented CNS algorithms more readily available.

VLSI Development: The neuromorphic circuits and architectures resulting from the research under the MURI award have been implemented in the MIT Lincoln Lab (MIT/LL) 3 tier FDSOI 3D CMOS technology.

Leveraging ONR support into other grants: The NGA and NSF CELEST grants were funded based on algorithms developed in significant measure under the MURI award.

ONR DATABASE STATISTICS

PI/Co-PI Information

0 PI/Co-PI Minority Women
0 PI/Co-PI Non-Minority Women
0 PI/Co-PI Minority Men
1 PI/Co-PI Non-Minority Men

Postdoctoral Information

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0 Postdoc Non-Minority Women
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0 Postdoc Non-Minority Men

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5 Graduate Non-Minority Women
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44 Graduate Non-Minority Men

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0 Undergrad Non-Minority Women
0 Undergrad Minority Men
0 Undergrad Non-Minority Men

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15	Books or Book Chapters
11	Technical Reports
129	Conference Abstracts and Proceedings
0	Patents Issued
0	Patents Pending

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Animal Subjects	NO
Recombinant DNA	NO
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Honors and Awards	49

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13. ABSTRACT *(Maximum 200 words)*
This MURI project develops a SMartVISION general-purpose autonomous neural system for vision, object recognition, and tracking applications to explain how the brain sees and to transfer new computer vision architectures into technology. SMartVISION predictions have been successfully tested in psychophysics and neurobiology labs. SMartVISION embodies a revolutionary paradigm shift in intelligent computation. It is designed to operate in real-time within noisy environments for which rules are not known and which contain rare but important events, unexpected events, incomplete data, irregular statistical drifts, and different amounts of morphological variability in objects to be detected and recognized. A companion architecture for distribute planning, decision, and action helps to actively acquire information by interacting with the SMartVISION system, including circuits to control attention shifts and eye movements to fixate regions of interest. SMartVISION is quantitatively simulating the dynamics of identified nerve cells, in known anatomical circuits, and the emergent behaviors that they control. It embodies qualitatively new computational paradigms with novel concepts and mechanisms for intelligent computing in response to a rapidly changing world, notably the paradigms of Laminar Computing and of Complementary Computing. These concepts and mechanisms have begun to break through old barriers in technology.

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