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The goal of this research program was to discover and develop real-time neural architectures capable of autonomously carrying out image processing and pattern recognition tasks in environments wherein noisy and unexpected events can occur. Such architectures are needed to cope with the fact that. in naturally occurring scenes. edges. texture. shading. size. stereo. and motion information are often overlaid and are viewed under variable illumination conditions. Special-purpose vision algorithms that can process only one of these types of information do not function well under naturally occurring conditions. The present work has analysed a large body of data from visual psychophysics and neurobiology in order to discover and test neural principles and mechanisms whereby such a general-purpose competence is achieved by humans and animals. These designs are embodied in multi-level neural networks which are defined by novel types of nonlinear dynamical systems. The networks are computationally characterized for use both in explaining biological data about vision and pattern recognition. and in implementing novel image processing circuits for use in technological applications. Predictions of the theory have also been successfully tested in our psychophysics laboratory.

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REAL-TIME IMAGE PROCESSING ARCHITECTURES FOR PERCEPTUAL GROUPING, DEPTH SEGREGATION, AND OBJECT RECOGNITION

FINAL REPORT

Professor Stephen Grossberg, Principal Investigator

June 1, 1988—August 31, 1991

U.S. Army Research Office
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STATEMENT OF THE PROBLEM

The goal of this research program was to discover and develop real-time neural architectures capable of autonomously carrying out image processing and pattern recognition tasks in environments wherein noisy and unexpected events can occur. Such architectures are needed to cope with the fact that. in naturally occurring scenes. edges. texture. shading. size. stereo. and motion information are often overlaid and are viewed under variable illumination conditions. Special-purpose vision algorithms that can process only one of these types of information do not function well under naturally occurring conditions. The present work has analysed a large body of data from visual psychophysics and neurobiology in order to discover and test neural principles and mechanisms whereby such a general-purpose competence is achieved by humans and animals. These designs are embodied in multi-level neural networks which are defined by novel types of nonlinear dynamical systems. The networks are computationally characterized for use both in explaining biological data about vision and pattern recognition. and in implementing novel image processing circuits for use in technological applications. Predictions of the theory have also been successfully tested in our psychophysics laboratory.

RESEARCH SUMMARY

Major progress was made on two types of problems: knowledge discovery and adaptive pattern recognition: and biological vision and image processing.

1. ART 3: Autonomous Learning and Distributed Memory Search

A new Adaptive Resonance Theory architecture. called ART 3 (Articles 5. 6. 7. 9) was designed by Carpenter and Grossberg. In common with ART 2. the ART 3 architecture is a self-organizing neural network capable of learning stable pattern recognition codes in real-time in response to arbitrary sequences of analog or binary input patterns. It does so by efficiently searching. testing. and learning hypotheses about the patterned data to which it is exposed.

In addition. ART 3 is capable of searching *hierarchies* of *distributed* pattern codes. This opens the possibility of simultaneously representing a pattern's most salient parts and wholes. and automatically reorganizing this representation based upon reinforcement feedback until it generates a maximally effective prediction. The architecture embodies new insights about how the dynamics of chemical transmitters and modulators act as a memory system capable of controlling a parallel search and hypothesis testing scheme.

2. Global Motion Segmentation

Grossberg and Mingolla (Articles 26. 27) have suggested a solution of the global aperture problem: namely. of how a coherent motion signal is imparted to all parts of a moving object. including parts that receive only locally ambiguous motion signals. This work clarifies. for example. how we can quickly see a sun-dappled leopard leaping under jungle trees. The sunshine and shadows upon the leopard's coat generate local motion signals in many directions that do not correspond to the overall direction of motion of the leopard's body. A similar competence is needed to rapidly detect camouflaged man-made objects moving in a cluttered background. Grossberg and Mingolla have suggested how these locally ambiguous signals are organized into a coherent global signal of the leopard's motion as a whole. and how challenging classical phenomena such as motion capture and induced motion may thereby be explained.

These analyses emphasize the fact that many. if not most. motion percepts are illusory percepts that can actively reorganize the data that reach our senses. Such an emphasis underscores the importance of explaining the large data base about apparent motion. We believe that such data should serve as a standard test of models purporting to provide computational insights about biological vision.

3. Explanation of Short-Range and Long-Range Apparent Motion Data

In this regard. Grossberg and Rudd have further developed this theory by explaining a wealth of data about apparent motion that other models have not been able to treat. In Articles 28 and 32. they describe further evidence for this new neural network theory of biological motion perception that is called a Motion Boundary Contour System. This theory clarifies why parallel streams $V1 \rightarrow V2$ and $V1 \rightarrow MT$ exist for static form and motion form processing among the areas $V1$. $V2$. and MT of visual cortex. The Motion Boundary Contour System consists of several parallel copies. such that each copy is activated by a different range of receptive field sizes. Each copy is further subdivided into two hierarchically organized subsystems: a Motion Oriented Contrast Filter. or MOC Filter. for preprocessing moving images: and a Cooperative-Competitive Feedback Loop. or CC Loop. for generating emergent boundary segmentations of the filtered signals. The article uses the MOC Filter to explain a variety of classical and recent data about short-range and long-range apparent motion percepts that have not yet been explained by alternative models. These data include split motion: reverse-contrast gamma motion: delta motion: visual inertia: group motion in response to a reverse-contrast Ternus display at short interstimulus intervals: speed-up of motion velocity as interflash distance increases or flash duration decreases: dependence of the transition from element motion to group motion on stimulus duration and size: various classical dependencies between flash duration. spatial separation. interstimulus interval. and motion threshold known as Korte's Laws: and dependence of motion strength on stimulus orientation and spatial frequency. These results supplement earlier explanations by the model of apparent motion data that other models have not explained: and a summary of how the main properties of other motion perception models can be assimilated into different parts of the Motion Boundary Contour System design.

4. A Symmetry Principle for Visual Form and Motion Perception

In Articles 21 and 24. Grossberg has provided a computational foundation for unifying this emerging theory of motion form perception with our previously developed theory of static form perception. Prior to this work. these two important subjects were treated as wholly separate in the scientific literature. Our analysis suggests that the visual cortex develops to realize a symmetry principle. called FM Symmetry (F = form. M = motion). Both the Static BCS and Motion BCS can be generated by FM Symmetry as two parallel halves of a larger system which satisfies three properties: namely. it (1) computes all possible way of symmetrically gating sustained cells with transient cells and (2) organizes these sustained-transient cells into opponent pairs of on-cells and off-cells such that (3) their output signals are insensitive to direction-of-contrast. The properties of FM Symmetry suggest how the $V1 \rightarrow V2 \rightarrow MT$ cortical stream helps to compute moving-form-in-depth. and how long-range apparent motion of illusory contours occurs.

An important consequence of FM Symmetry is its explanation of how the static form and motion form systems generate different geometries of perceptual space that are familiar from daily experience. In particular. cell pairs in the static form system define opponent *orientations* that differ by 90°. whereas cell pairs in the motion form system define opponent *directions* that differ by 180°. Changes in visual inputs can cause a rapid antagonistic rebound to occur between opponent members of each pair. with on-cell activation being displaced by off-cell activation. These antagonistic rebounds help to prevent smearing of percepts in response to rapidly changing scenes by resetting resonating boundary segmentations which could otherwise persist for a long time. In so doing. antagonistic rebounds can cause negative aftereffects. such as the MacKay illusion in static form perception. and the waterfall illusion and long-range motion aftereffects in motion form perception.

5. Visual Psychophysics

In Articles 41. 42. and 43. experimental tests of various aspects of the Motion Boundary Contour System theory of human motion perception were reported. Quantitative analyses of the dependence of stimulus contrast and scale on the probability of perceived direction of movement as a function of spatial separation and interstimulus interval were performed. The results verified the spatial and temporal form factors for apparent motion proposed in the theory. The data clarified the contrast and scale dependence of these form factors. Earlier data was insufficient for this purpose, because less sophisticated experimental techniques were employed in early studies. and because a very large number of trials had to be collected for individual subjects. in order to perform mathematical analyses of the data which could be related to parameters of the theoretical model.

Article 41 described experimental conditions in which the minimum interstimulus interval for perceived motion either is or is not dependent on the spatial separation between the stimuli matched by the motion detector. The fact that this minimum interstimulus interval is not dependent on the spatial parameters of the stimulus when the stimulus duration is long was used to argue against a traditional spreading activation model of apparent motion threshold data, and in favor of a feed-forward motion receptive field model such as the Motion BCS. In Article 43, we showed that, when observer bias occurs in our forced-choice motion direction judgment task, it appears to act as a multiplicative gating of the signal-to-noise ratio of the mechanisms tuned to a particular direction of motion. This previously unnoted fact has important implications both for the construction of a correct model of the neural mechanisms involved in motion perception, and for understanding the interaction between preattentive and attentive processes involved in motion perception.

Further modelling studies in vision analysed aspects of visual detection that depend upon stochastic properties of neural processes. In Article 39, a theory of threshold vision was proposed that explains a greater amount of the visual sensitivity data base as a result of light fluctuations than has previously been thought possible. The article proposes a statistical theory of contrast encoding by the visual system, that reduces to a standard model in the deterministic limit. In the paper, recent mathematical theory and techniques developed in theoretical neurobiology are applied to the explanation of visual phenomena for the first time.

LIST OF PUBLICATIONS

Contract ARO DAAL-03-88-K-0088

June 1, 1988—August 31, 1991

BOOKS

1. Grossberg. S. and Kuperstein. M. (1989). **Neural dynamics of adaptive sensory-motor control: Expanded edition.** Elmsford. NY: Pergamon Press. (*+)
2. Commons. M.. Grossberg. S.. and Staddon. J.E.R. (Eds.) (1991). **Neural network models of conditioning and action.** Hillsdale. NJ: Erlbaum Associates. (*+)
3. Carpenter. G.A. and Grossberg. S. (Eds.). (1991). **Pattern recognition by self-organizing neural networks.** Cambridge. MA: MIT Press. (*+)

ARTICLES

1. Bressan. P. and Rudd. M.E. (in preparation). Failure to observe Korte's 3rd law of apparent motion with long flash durations. To be submitted to *Science*.
2. Bullock. D.. Carpenter. G.A.. and Grossberg. S. (1989). Self-organizing neural network architectures for adaptive pattern recognition and robotics. In V. Milutinovic and P. Antognetti (Eds.). **Neural networks: Concepts, applications, and implementations.** Englewood Cliffs. NJ: Prentice Hall. pp. 33–53. (*+)
3. Carpenter. G.A. and Grossberg. S. (1988). Self-organizing neural network architectures for real-time adaptive pattern recognition. In H. Haken (Ed.). **Neural and synergetic computers.** New York: Springer-Verlag. pp. 42–74. (*+)
4. Carpenter. G.A. and Grossberg. S. (1990). Self-organizing neural network architectures for real-time adaptive pattern recognition. In S. F. Zornetzer. J. L. Davis. and C. Lau (Eds.). **An introduction to neural and electronic networks.** New York: Academic Press. pp. 455–478. (*+)
5. Carpenter G.A. and Grossberg. S. (1990). ART 3: Hierarchical search using chemical transmitters in self-organizing pattern recognition architectures. *Neural Networks*. **3**. 129–152. (*+)
6. Carpenter. G.A. and Grossberg. S. (1990). Adaptive resonance theory: Neural network architectures for self-organizing pattern recognition. In R. Eckmiller. G. Hartmann. and G. Hauske (Eds.). **Parallel processing in neural systems and computers.** Amsterdam: Elsevier. pp. 383–389. (*+@%)
7. Carpenter. G.A. and Grossberg. S. (1990). ART 3 hierarchical search: Chemical transmitters in self-organizing pattern recognition architectures. In M. Caudill (Ed.). **Proceedings of the international joint conference on neural networks.** January. **II**. 30–34. Hillsdale. NJ: Erlbaum Associates. (*+)
8. Carpenter. G.A. and Grossberg. S. (1990). Neural dynamics of category learning and recognition: Structural invariants. evoked potentials. and reinforcement. In M. Commons. R. Herrnstein, S. Kosslyn. and D. Mumford (Eds.). **Computational and clinical approaches to pattern recognition and concept formation.** Hillsdale. NJ: Erlbaum Associates. (*+)

9. Carpenter. G.A. and Grossberg, S. (1991). Attention. resonance. and transmitter dynamics in models of self-organizing cortical networks for recognition learning. In A. V. Holden and V. I. Kryukov (Eds.). **Neurocomputers and attention.** Manchester: Manchester University Press. (*+ã%)

10. Carpenter. G.A. and Grossberg. S. (1991). Adaptive resonance theory: Self-organizing neural network architectures for pattern recognition and hypothesis testing. In **Encyclopedia of artificial intelligence, Second edition.** New York: Wiley and Sons. (*%ã+)

11. Carpenter. G.A., Grossberg, S., and Mehanian, C. (1989). Invariant recognition of cluttered scenes by a self-organizing ART architecture: CORT-X boundary segmentation. *Neural Networks*. **2**. 169–181. (*+)

12. Carpenter. G.A.. Grossberg, S.. and Reynolds. J.H. (1991). ARTMAP: Supervised real-time learning and classification of nonstationary data by a self-organizing neural network. *Neural Networks*. **4**. 565–588. (*%ã+)

13. Carpenter. G.A.. Grossberg. S., and Reynolds. J.H. (1991). A self-organizing ARTMAP neural architecture for supervised learning and pattern recognition. In R. Mammone and Y. Zeevi (Eds.). **Neural networks: Theory and applications.** New York: Academic Press. (*%ã+)

14. Carpenter. G.A.. Grossberg. S.. and Reynolds. J.H. (1991). A neural network architecture for fast on-line supervised learning and pattern recognition. In H. Wechsler (Ed.). **Neural networks for human and machine perception.** New York: Academic Press. (*%ã+)

15. Carpenter. G.A.. Grossberg. S., and Reynolds. J.H. (1991). ARTMAP: A self-organizing neural network architecture for fast supervised learning and pattern recognition. In O. Simula (Ed.). **Proceedings of the international conference on artificial neural networks.** Amsterdam: Elsevier. (*%ã+)

16. Carpenter. G.A.. Grossberg. S.. and Reynolds. J.H. (1991). ARTMAP: Supervised real-time learning and classification of nonstationary data by a self-organizing neural network. In **Proceedings of the international joint conference on neural networks.** Seattle. **I**. 863–868. Piscataway. NJ: IEEE Service Center. (*%ã+)

17. Carpenter. G.A.. Grossberg. S.. and Rosen. D.B. (1991). ART 2-A: An adaptive resonance algorithm for rapid category learning and recognition. *Neural Networks*. **4**. 493–504. (*%ã+)

18. Carpenter. G.A.. Grossberg. S.. and Rosen. D.B. (1991). ART 2-A: An adaptive resonance algorithm for rapid category learning and recognition. In **Proceedings of the international joint conference on neural networks.** Seattle. **II**. 151–156. Piscataway. NJ: IEEE Service Center. (*%ã+)

19. Carpenter. G.A.. Grossberg, S., and Rosen. D.B. (1991). Fuzzy ART: An adaptive resonance algorithm for rapid. stable classification of analog patterns. In **Proceedings of the international joint conference on neural networks.** Seattle. **II**. 411–420. Piscataway. NJ: IEEE Service Center. (*%ã+)

20. Grossberg. S. (1990). Attention and recognition learning by adaptive resonance. *Behavioral and Brain Sciences*. **13**. 241–242. (*)

21. Grossberg. S. (1990). Neural FACADES: Visual representations of static and moving form-and-color-and-depth. *Mind and Language* (Special issue on Understanding Vision). **5**. 411–456. (*ã&)

22. Grossberg, S. (1990). Preattentive visual perception: Emergent segmentation and featural filling-in. In L. Spillmann and J. S. Werner (Eds.). **Visual perception: The neurophysiological foundations.** New York: Academic Press. pp. 439–447. (*+)

23. Grossberg, S. (1990). Self-organizing architectures for motion perception. adaptive sensory-motor control, and associative mapping. In M. Caudill (Ed.). **Proceedings of the interna-**

tional joint conference on neural networks. January, **II.** 26–29. Hillsdale, NJ: Erlbaum Associates. (*+)

24. Grossberg, S. (1991). Why do parallel cortical systems exist for the perception of static form and moving form? *Perception and Psychophysics*, **49**, 117–141. (*+)

25. Grossberg, S. and Marshall, J. (1989). Stereo boundary fusion by cortical complex cells: A system of maps, filters, and feedback networks for multiplexing distributed data. *Neural Networks*, **2**, 29–51. (*+)

26. Grossberg, S. and Mingolla, E. (1990). Neural dynamics of motion segmentaiton: Direction field, apertures, and resonant grouping. In M. Caudill (Ed.), **Proceedings of the international joint conference on neural networks.** January, **I.** 11–14. Hillsdale, NJ: Erlbaum Associates. (*)

27. Grossberg, S. and Mingolla, E. (1990). Neural dynamics of motion segmentation. In **Proceedings of graphics interface/vision interface '90.** Toronto: Canadian Information Processing Society, pp. 112–119. (*)

28. Grossberg, S. and Rudd, M.E. (1989). A neural architecture for visual motion perception: Group and element apparent motion. In M. Caudill (Ed.), **Proceedings of the international joint conference on neural networks.** June, **I.** 195–199. Piscataway, NJ: IEEE Service Center. (*+)

29. Grossberg, S. and Rudd, M.E. (1989). Neural dynamics of visual motion perception: Group and element apparent motion. *Investigative Ophthalmology Supplement*, **30**, 73. (*+)

30. Grossberg, S. and Rudd, M.E. (1989). A neural architecture for visual motion perception: Group and element apparent motion. *Neural Networks*, **2**, 421–450. (*+)

31. Grossberg, S. and Rudd, M.E. (1990). Cortical dynamics of visual motion perception: Short- and long-range motion. *Investigative Ophthalmology Supplement*, **31**, 529. (*+)

32. Grossberg, S. and Rudd, M.E. (1991). Cortical dynamics of visual motion perception: Short-range and long-range motion. *Psychological Review*, in press. (*+)

33. Grossberg, S. and Rudd, M.E. (1991). A neural theory of visual motion perception. In B. Blum (Ed.), **Channels in the visual nervous system: Neurophysiology, psychophysics, and models.** Tel Aviv: Freund Publishing House Ltd., in press. (*@)

34. Grossberg, S. and Somers, D. (1991). Synchronized oscillations during cooperative feature linking in a cortical model of visual perception. *Neural Networks*, **4**, 453–466. (*@)

35. Grossberg, S. and Somers, D. (1991). Synchronized oscillations during cooperative feature linking in visual cortex. In O. Simula (Ed.), **Proceedings of the international conference on artificial neural networks.** Amsterdam: Elsevier. (*@)

36. Grossberg, S. and Somers, D. (1991). Synchronized oscillations during cooperative feature linking in visual cortex. In **Proceedings of the international joint conference on neural networks.** Seattle, **II.** 249–254. Piscataway, NJ: IEEE Service Center. (*@)

37. Grossberg, S. and Todorović, D. (1989). Solving the brightness-from-luminance problem: A neural architecture for invariant brightness perception. In S. J. Hanson and C. Olson (Eds.), **Connectionist modeling and brain function: The developing interface.** Cambridge, MA: MIT Press. (*+)

38. Grossberg, S. and Wyse, L. (1991). Invariant recognition of cluttered scenes by a self-organizing ART architecture: Figure-ground separation. In **Proceedings of the international joint conference on neural networks.** Seattle, **I.** 633–638. Piscataway, NJ: IEEE Service Center. (*@&)

39. Rudd, M.E. (1990). A variable integration time model of threshold versus intensity curves. *Journal of the Optical Society of America*, in press. (*+)

40. Rudd, M.E. (in press). Review of **Stochastic processes in the neurosciences** by H. C. Tuckwell for *Journal of Mathematical Psychology*.

41. Rudd, M.E. and Bressan, P. (in preparation). Quantitative analyses of apparent motion thresholds: Dependence on interstimulus interval, luminance, and size. To be submitted to *Vision Research.*

42. Rudd, M.E. and Bressan, P. (in press). Quantitative analyses of apparent motion thresholds: Dependence on spatial separation, luminance, and size. Submitted to *Vision Research.*

43. Rudd, M.E. and Bressan, P. (in preparation). Quantitative analysis of directional bias in an apparent motion task. To be submitted to *Vision Research.*

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