AD-A277 526

ATION PAGE Approved for public release; distribution unlimited.

Form Approved OMB No. 0704-0188

to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, wing the collection of information. Send comments regarding this burden estimate or any other aspect of this n. to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson e of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

DATE
January 1994

3. REPORT TYPE AND DATES COVERED
annual technical 5/1/92--4/30/93

4. TITLE AND SUBTITLE
A self-organizing neural network architecture for auditory and speech perception with applications to acoustic and other temporal prediction problems

5. FUNDING NUMBERS
F49620-92-J-0225
61102F
2313
AS

6. AUTHOR(S)
Stephen Grossberg and Michael Cohen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boston University
Center for Adaptive Systems
and
Department of Cognitive and Neural Systems
Boston, MA 02215

8. PERFORMING ORGANIZATION REPORT NUMBER
AEOSR-TR- 94 0107

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
Bolling AFB, DC 20332

Dr. Tangney

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

13PP

94-09431

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This project is developing autonomous neural network models for the real-time perception and production of acoustic and speech signals. A new acoustic filter was developed to show how coarticulated context-sensitive auditory signals can be separated and represented in a more context-independent fashion, thereby easing the recognition problem. Parallel processing streams sensitive to sustained and transient signals are used, as in vision. A model of working memory was developed that automatically compensates for variable acoustic or speech rates. The model shows how invariance of the short term storage of variable-rate acoustic streams can explain data about categorical boundary shifts when the distributions of silent intervals or of vowel durations are altered. New learning and categorization nets were shown to discriminate vowels with comparable accuracy but much higher compression than alternative methods. Models of skilled motor control were developed to clarify how speech and arm movements can be planned and flexibly modified by task requirements. Studies of neural oscillators suggest how rhythmic behaviors relevant to perception and action, notably synchronous oscillations, may be generated and controlled.

14. SUBJECT TERMS

15. NUMBER OF PAGES
13 pages

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified		

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

94 3 25 121

PUBLICATIONS PARTIALLY SUPPORTED BY THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Contract AFOSR F49620-92-J-0225

MAY 1, 1992—APRIL 30, 1993

Center for Adaptive Systems
and
Department of Cognitive and Neural Systems
Boston University

1. Boardman, I., Cohen, M.A., and Grossberg, S. (1993). Variable rate working memories for phonetic categorization and invariant speech perception. **Technical Report CAS/CNS-TR-93-008**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **III**, 2–5. Hillsdale, NJ: Erlbaum Associates. (%&)
2. Bradski, G., Carpenter, G.A., and Grossberg, S. (1992). STORE working memory networks for storage and recall of arbitrary temporal sequences. **Technical Report CAS/CNS-TR-92-028**, Boston University. Submitted for publication. (*#%+&)
3. Bradski, G. and Cohen, M.A. (1993). A preliminary look at a fast learning architecture for speaker independent speech recognition. In **Proceedings of the world congress on neural networks**, Portland, **III**, 37–39. Hillsdale, NJ: Erlbaum Associates. (+@)
4. Bullock, D., Grossberg, S., and Mannes, C. (1993). The VITEWRITE model of handwriting production. **Technical Report CAS/CNS-TR-93-011**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **I**, 507–511. Hillsdale, NJ: Erlbaum Associates. (%+&)
5. Carpenter, G.A. and Govindarajan, K.K. (1993). Evaluation of speaker normalization methods for vowel recognition using fuzzy ARTMAP and K-NN. **Technical Report CAS/CNS-TR-93-013**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **III**, 10–15. Hillsdale, NJ: Erlbaum Associates. (#%+&)
6. Carpenter, G.A. and Govindarajan, K.K. (1993). Speaker normalization methods for vowel recognition: Comparative analysis using neural network and nearest neighbor classifiers. **Technical Report CAS/CNS-TR-93-039**, Boston University. Submitted for publication. (%#+@)
7. Carpenter, G.A. and Grossberg, S. (1993). Integrating symbolic and neural processing in a self-organizing architecture for pattern recognition and prediction. **Technical Report CAS/CNS-TR-93-002**, Boston University. In V. Honavar and L. Uhr (Eds.), **Integrating symbol processors connectionist networks for artificial intelligence and cognitive modelling**. New York: Academic Press. (#%+&)
8. Cohen, M.A. (1993). Neural network models of speech and language perception and recognition. In **Proceedings of the world congress on neural networks**, Portland, **III**, 1. Hillsdale, NJ: Erlbaum Associates.
9. Cohen, M.A., Grossberg, S., and Pribe, C. (1993). Neural control of interlimb coordination and gait timing in bipeds and quadrupeds. **Technical Report CAS/CNS-TR-93-004**, Boston University. Submitted for publication. (@%&)

10. Cohen, M.A., Grossberg, S., and Pribe, C. (1993). A neural pattern generator that exhibits arousal-dependent human gait transitions. **Technical Report CAS/CNS-TR-93-017**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **IV**, 285–288. Hillsdale, NJ: Erlbaum Associates. (*%+&)

11. Cohen, M.A., Grossberg, S., and Pribe, C. (1993). Frequency-dependent phase transitions in the coordination of human bimanual tasks. **Technical Report CAS/CNS-TR-93-018**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **IV**, 491–494. Hillsdale, NJ: Erlbaum Associates. (*%+&)

12. Cohen, M.A., Grossberg, S., and Pribe, C. (1993). Quadruped gait transitions from a neural pattern generator with arousal modulated interactions. **Technical Report CAS/CNS-TR-93-019**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **II**, 610–613. Hillsdale, NJ: Erlbaum Associates. (*%+&)

13. Cohen, M.A., Grossberg, S., and Wyse, L. (1992). A neural network spectral model of pitch detection and representation. Submitted for publication. (%&)

14. Grossberg, S. (1993). Self-organizing neural networks for stable control of autonomous behavior in a changing world. In J.G. Taylor (Ed.), **Mathematical approaches to neural networks**. Amsterdam: Elsevier Science Publishers, pp. 139–197. (%&)

15. Grossberg, S. and Grunewald, A. (1993). Statistical properties of single and competing nonlinear fast-slow oscillations in noise. **Technical Report CAS/CNS-TR-93-022**, Boston University. In **Proceedings of the world congress on neural networks**, Portland, **IV**, 303–307. Hillsdale, NJ: Erlbaum Associates. (%+&)

* Also supported in part by the AFOSR URI.

@ Also supported in part by the Army Research Office.

% Also supported in part by ARPA.

Also supported in part by British Petroleum.

+ Also supported in part by the National Science Foundation.

& Also supported in part by the Office of Naval Research.

RESEARCH SUMMARIES

Pitch Perception

One of the major human auditory abilities is the effortless identification of multiple speakers while simultaneously understanding the content of their speech. This content is of course speaker independent. There is considerable evidence that an important cue for the segregation of speech by speaker is the pitch of the utterance.

Cohen, Grossberg, and Wyse have developed a neural model of pitch perception, and have submitted this work for publication. This model provides a unified explanation of the key experimental data on pitch perception and is part of our theory of auditory object recognition. The model computes a spatial representation of pitch as one of several steps in our development of a theory of auditory source segregation and streaming. Simulated data include pitch perception with mistuned or missing components, shifted harmonics, and various types of noise; the auditory dominance region; octave shifts to ambiguous stimuli; and Shepard auditory barberpole illusions. The model provides a basis for linking featural and spatial information to rapidly locate and bind together the auditory signals that correspond to a target in space. Research on such target localization has begun, as noted in the next paragraph. [Article 13]

Design of Variable-Rate Working Memories and Categorization Networks

An important problem in speech recognition is the identification, selection, and coherent grouping of speech units from a continuously fluctuating acoustic stream. Of particular importance in this process is the influence of current auditory context on prior representations which have already been partially constructed. Most models of speech recognition work strictly forward in time, and have considerable difficulty in dealing with such backwards effects, especially when speech rate is variable. A diagnostic set of data from Repp, among others, shows that the prior distribution of silence in the speech waveform plays a critical role in determining whether a single stop consonant (e.g. /aga/) or a stop consonant cluster (e.g. /agpa/) is heard. These data probe the conditions under which phonetic boundaries are perceived. They illustrate that the speech code is not derived directly from bottom-up filtered data, but is, rather, an emergent property of bottom-up interactions with learned top-down expectations.

This project begins to model the interaction between a working memory that temporarily stores speech tokens and its feedback interactions with a speech categorization network.

The first project showed how a working memory could be designed such that all possible groupings of stored items could be learned in a stable fashion, even if a grouping was later stored and learned as part of a larger grouping. Thus the word MY is not forgotten when it is later learned as part of the word MYSELF. This was shown for *arbitrary* temporal streams of data, occurring with arbitrary rates, delays, and repetitions.

Next it was shown how such a working memory could be modified such that its integration rate automatically adjusts to generate a representation that is independent of the input rate. This invariance property is used to explain key properties of the Repp data. Thus the variability of categorical recognition boundaries can be derived from the invariance of the working memory code in response to variable-rate acoustic signals.

The model also clarifies other backward effects in speech, such as when a stop (e.g. /ba/) percept is transformed into a glide (e.g. /wa/) percept by varying the duration of the subsequent vowel. [Articles 1 and 2]

Speech Filtering and Coarticulation

The rate of reception of normal spoken language places severe demands on the sensory, motor, and cognitive mechanisms which control the speech production process. The vocal musculature often cannot keep up with the rate of transmission of spoken speech. Nature's solution to the motoric problem is to overlap significant parts of gestural motion for adjacent speech stops and consonants, a phenomenon called coarticulation.

This coarticulation creates corresponding perceptual problems, because the acoustic stream for the same phonetic percept is of necessity context-dependent. An early stage of auditory neural processing must be able to separate and represent these segments in a context-independent fashion to disambiguate these coarticulations.

Parallel processing streams that are sensitive to sustained and transient features are suggested to play such a role in speech perception. Analogous parallel streams are known to occur in vision. We are preparing a paper which models these auditory sustained and transient mechanisms and shows how their combination can disambiguate sonorant (vowels [/i/], nasal [m,n], and glides [y,w]) from non-sonorant (stops /t/ and fricatives /s,z/) phonetic classes. Furthermore, these detectors can distinguish between the major subcategories of these classes. This work hereby proposes a partial description of how the human auditory apparatus solves the perceptual problem caused by coarticulation. Later processing is greatly simplified by this processing stage.

Speaker Normalization in Speech

A total of 32 intrinsic and 128 extrinsic methods of vowel normalization have been analysed on the Peterson-Barney database, using the K-Nearest Neighbor and Fuzzy ARTMAP pattern classifiers using 10 nearest neighbors throughout. A total of 128 extrinsic and 28 extrinsic methods were used in the classification.

Fuzzy ARTMAP is a self-organizing neural network classifier, developed recently in our group by Professors Carpenter and Grossberg with several PhD students. It is capable of real-time hypothesis testing to discover and learn recognition categories whose number, shape, and size adapt to the statistics of an arbitrary nonstationary data stream. In this preliminary study, K-NN performed slightly better than Fuzzy ARTMAP because it exhaustively stores all the data. K-NN also needed 10 times as much memory to gain this slight advantage. The much improved compression will be of great importance in large database problelms. More powerful ART systems also promise to achieve better performance and compression. The optimal intrinsic normalization scheme was Bark differences in frequency. The optimal extrinsic normalization scheme involved choosing a best linear transformation of the data. [Article 5]

Handwriting Production

The psychophysical properties of speech articulator movements and arm reaching movements share many common features. Models of skilled arm movement control thus promise to shed light on how spoken language is generated. This knowledge, in turn, can help to clarify how articulatory constraints may influence the sppeech perception process.

The VITEWRITE model of Bullock, Grossberg, and Mannes suggests how complex handwritten movements may be flexibly generated with different sizes, speeds, and styles. To achieve this competence, it is shown how a suitably designed working memory interacts via nonlinear feedback with a multijoint trajectory generator that is modulated by volitional scalar GO (speed) and GRO (size) signals. It is also shown how a redundant manipulator simplifies the control problem. A new concept of motor program is hereby developed for the control of multiple motor constraints. Neural data about frontal cortex, motor cortex, parietal cortex, and basal ganglia are clarified by the model. Psychophysical data about handwriting control, such as the isochrony principle, asymmetric velocity profiles, and the two thirds power law relating velocity to curvature arise as emergent properties of model interactions. [Article 4]

Central Pattern Generators

Rhythmic processes are important in acoustical and speech perception and production. A class of central pattern generator models was developed to explain behavioral data about human and animal gaits and their transitions. Simulated data include all the cat gait transitions (walk-trot-pace-gallop), the human walk-run transition, and the transition from anti-phase movements to synchronous in-phase movements during increasingly rapid finger oscillations. These analyses clarified how a volitional GO, or speed, signal can interact with suitably designed feedback networks to generate only the desired gaits and transitions, quickly and stably. They also clarified how switches from either anti-phase to in-phase, or in-phase to anti-phase movements can be generated as the GO signal increases in different parameter ranges of a single network. [Articles 9–12]

Synchronous Dynamics of Nonlinear Oscillators

In both speech and neural processing, a role for synchronous binding of spatially distributed features into coherent perceptual units has been psychophysically and neurally reported. Ths study modeled how neural networks could be designed to achieve rapid synchronization of distributed data even in high levels of cellular noise. It was also shown how stochastic resonance could arise in the model, thereby improving its signal-to-noise ratio in noise. [Article 15]

SELECTED ABSTRACTS

VARIABLE RATE WORKING MEMORIES FOR PHONETIC CATEGORIZATION AND INVARIANT SPEECH PERCEPTION

Ian Boardman, Michael Cohen, and Stephen Grossberg

Technical Report CAS/CNS-TR-93-008, Boston University
In **Proceedings of the World Congress on Neural Networks**
Hillsdale, NJ: Erlbaum Associates, 1993, **III**, pp. 2–5

Abstract

Speech can be understood at widely varying production rates. A working memory is described for short-term storage of temporal lists of input items. The working memory is a cooperative-competitive neural network that automatically adjusts its integration rate, or gain, to generate a short-term memory code for a list that is independent of item presentation rate. Such an invariant working memory model is used to simulate data of Repp (1980) concerning the changes of phonetic category boundaries as a function of their presentation rate. Thus the variability of categorical boundaries can be traced to the temporal invariance of the working memory code.

Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225 and AFOSR 90-0128), ARPA (ONR N00014-92-J-4015), and the Office of Naval Research (ONR N00014-91-J-4100).

STORE WORKING MEMORY NETWORKS FOR STORAGE AND RECALL OF ARBITRARY TEMPORAL SEQUENCES

Gary Bradski†, Gail A. Carpenter‡, and Stephen Grossberg§

Technical Report CAS/CNS-TR-92-028, Boston University
Submitted to *Biological Cybernetics*

Abstract

Neural network models of working memory, called **S**ustained **T**emporal **O**rder **RE**current (STORE) models, are described. They encode the invariant temporal order of sequential events in short term memory (STM) in a way that mimics cognitive data about working memory, including primacy, recency, and bowed order and error gradients. As new items are presented, the pattern of previously stored items is invariant in the sense that relative activations remain constant through time. This invariant temporal order code enables all possible groupings of sequential events to be stably learned and remembered in real time, even as new events perturb the system. Such a competence is needed to design self-organizing temporal recognition and planning systems in which any subsequence of events may need to be categorized in order to control and predict future behavior or external events. STORE models show how arbitrary event sequences may be invariantly stored, including repeated events. A preprocessor interacts with the working memory to represent event repeats in spatially separate locations. It is shown why at least two processing levels are needed to invariantly store events presented with arbitrary durations and interstimulus intervals. It is also shown how network parameters control the type and shape of primacy, recency, or bowed temporal order gradients that will be stored.

† Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0128) and the Office of Naval Research (ONR N00014-91-J-4100 and ONR N00014-92-J-1309).

‡ Supported in part by British Petroleum (BP 89A-1204), ARPA (AFOSR 90-0083 and ONR N00014-92-J-4015), the National Science Foundation (NSF IRI-90-00530), and the Office of Naval Research (ONR N00014-91-J-4100).

§ Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225), ARPA (AFOSR 90-0083 and ONR N00014-92-J-4015) and the Office of Naval Research (ONR N00014-91-J-4100 and ONR N00014-92-J-1309).

EVALUATION OF SPEAKER NORMALIZATION METHODS FOR VOWEL RECOGNITION USING FUZZY ARTMAP AND K-NN

Gail A. Carpenter† and Krishna K. Govindarajan‡

Technical Report CAS/CNS-TR-93-013, Boston University
In **Proceedings of the World Congress on Neural Networks**
Hillsdale, NJ: Erlbaum Associates, 1993, **III**, pp. 10–15

Abstract

A procedure that uses fuzzy ARTMAP and K-Nearest Neighbor (K-NN) categorizers to evaluate intrinsic and extrinsic speaker normalization methods is described. Each classifier is trained on preprocessed, or normalized, vowel tokens from about 30% of the speakers of the Peterson-Barney database, then tested on data from the remaining speakers. Intrinsic normalization methods included one nonscaled, four psychophysical scales (bark, bark with end-correction, mel, ERB), and three log scales, each tested on four different combinations of the fundamental (F_0) and the formants (F_1, F_2, F_3). For each scale and frequency combination, four extrinsic speaker adaptation schemes were tested: centroid subtraction across all frequencies (CS), centroid subtraction for each frequency (CSi), linear scale (LS), and linear transformation (LT). A total of 32 intrinsic and 128 extrinsic methods were thus compared. Fuzzy ARTMAP and K-NN showed similar trends, with K-NN performing somewhat better and fuzzy ARTMAP requiring about 1/10 as much memory. The optimal intrinsic normalization method was bark scale, or bark with end-correction, using the differences between all frequencies (Diff All). The order of performance for the extrinsic methods was LT, CSi, LS, and CS, with fuzzy ARTMAP performing best using bark scale with Diff All; and K-NN choosing psychophysical measures for all except CSi.

† Supported in part by British Petroleum (BP 89A-1204), ARPA (AFOSR (90-0083 and ONR N00014-92-J-4015), the National Science Foundation (NSF IRI-90-00530), and the Office of Naval Research (ONR N00014-91-J-4100).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225), ARPA (ONR N00014-92-J-4015), and the National Science Foundation (NSF IRI-90-00530).

NEURAL CONTROL OF INTERLIMB COORDINATION AND GAIT TIMING IN BIPEDS AND QUADRUPEDS

Michael A. Cohen†, Stephen Grossberg‡, and Christopher Pribe§

Technical Report CAS/CNS-TR-93-004, Boston University
Submitted to *Journal of Neurophysiology*

Abstract

1) A family of central pattern generators, called GO Gait Generators, is described in which both the frequency and the relative phase of oscillations are controlled by a scalar arousal or GO signal that instantiates the will to act. The model cells obey shunting membrane equations, and interact via fast excitatory feedback signals and slow inhibitory feedback signals, orga ized as an on-center off-surround anatomy.

2) With two excitatory cells, or cell populations, the model describes an opponent processing network in which both in-phase and anti-phase oscillations can occur at different arousal levels. This two-channel oscillator can also produce phase transitions from either in-phase to anti-phase oscillations, or anti-phase to in-phase oscillations, in different parameter ranges, as the GO signal increases.

3) The two-channel oscillator is used to simulate data from human bimanual finger coordination tasks in which anti-phase oscillations at low frequencies spontaneously switch to in-phase oscillations at high frequencies, in-phase oscillations can be performed both at low and high frequencies, phase fluctuations occur at the anti-phase in-phase transition, and a "seagull effect" of larger errors occurs at intermediate phases. When driven by environmental patterns with intermediate phase relationships, the model's output exhibits a tendency to slip toward purely in-phase and anti-phase relationships as observed in humans subjects

4) A four-channel oscillator is used to simulate quadruped vertebrate gaits, including the amble, the walk, all three pairwise gaits (trot, pace, and gallop), and the pronk. Spatial or temporal asymmetries in oscillator activation by the GO signal can trigger these transitions. Rapid transitions are simulated in the order—walk, trot, pace, and gallop—that occurs in the cat.

5) This precise switching control is achieved by using GO-dependent modulation of the model's inhibitory interactions that generates a different functional connectivity in a single network at different arousal levels. Such task-specific modulation of functional connectivity in neural pattern generators has been experimentally reported in invertebrates. A role for such a mechanism in gait-switching is predicted to occur in vertebrates.

6) A four channel oscillator can generate the two standard human gaits: the walk and the run. Although these two gaits are qualitatively different, they both have the same limb order and may exhibit oscillation frequencies that overlap. The model simulates the walk and the run via qualitatively different waveform shapes. The fraction of cycle that activity is above threshold quantitatively distinguishes the two gaits, much as the duty cycles of the feet are longer in the walk than in the run.

† Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0128 and AFOSR F49620-92-J-0225).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR 90-0175 and AFOSR F49620-92-J-0225), the National Science Foundation (NSF IRI-90-24877), and the Office of Naval Research (ONR N00014-92-J-1309).

§ Supported in part by the Army Research Office (ARO DAAL03-88-K-0088), the Advanced Research Projects Agency (AFOSR 90-0083), the National Science Foundation (NSF IRI-90-24877), and the Office of Naval Research (ONR N00014-92-J-1309).

A NEURAL NETWORK SPECTRAL MODEL OF PITCH DETECTION AND REPRESENTATION

Michael A. Cohen†, Stephen Grossberg‡, and Lonce Wyse*

Submitted to *Journal of the Acoustical Society of America*

Abstract

A neural network model of pitch perception, called the Spatial Pitch Network or SPINET model, is developed and analysed. The model neurally instantiates ideas from the spectral pitch modeling literature and joins them to basic neural network signal processing designs to simulate a broader range of perceptual pitch data than previous spectral models. The components of the model are interpreted as peripheral mechanical and neural processing stages, which are capable of being incorporated into a larger network architecture for segmenting multiple sound sources in the environment.

The core of the new model transforms a spectral representation of an acoustic source into a spatial distribution of pitch strengths. The SPINET model uses a weighted "harmonic sieve" whereby the strength of activation of a given pitch depends upon a weighted sum of narrow regions around the harmonics of the nominal pitch value, and higher harmonics contribute less to a pitch than lower ones. Suitably chosen harmonic weighting functions enable computer simulations of pitch perception data involving mistuned components, shifted harmonics, and various types of continuous spectra including rippled noise. It is shown how the weighting functions produce the dominance region, how they lead to octave shifts of pitch in response to ambiguous stimuli, and how they lead to a pitch region in response to the octave-spaced "Shepard" tone complexes without the use of attentional mechanisms to limit pitch choices. An on-center off-surround network in the model helps to produce noise suppression, partial masking, and edge pitch. A method is described for relating the model's pitch activation functional to statistical human performance and for comparing the network model with Goldstein's statistical Optimum Processor Theory. Finally, it is shown how peripheral filtering and short term energy measurements produce a model pitch estimate that is sensitive to certain component phase relationships.

† Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225), ARPA (ONR N00014-92-J-4015), and the Office of Naval Research (ONR N00014-91-J-4100).

Supported in part by the American Society for Engineering Education, and the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225).

STATISTICAL PROPERTIES OF SINGLE AND COMPETING NONLINEAR FAST-SLOW OSCILLATORS IN NOISE

Stephen Grossberg† and Alexander Grunewald‡

Technical Report CAS/CNS-TR-93-022, Boston University
In **Proceedings of the World Congress on Neural Networks**
Hillsdale, NJ: Erlbaum Associates, 1993, **IV**, 303–307

Abstract

Statistical properties of fast-slow Ellias-Grossberg oscillators are studied in response to deterministic and noisy inputs. Oscillatory responses remain stable in noise due to the slow inhibitory variable, which establishes an adaptation level that centers the oscillatory responses of the fast excitatory variable to deterministic and noisy inputs. Competitive interactions between oscillators improve the stability in noise. Although individual oscillation amplitudes decrease with input amplitude, the average total activity increases with input amplitude, thereby suggesting that oscillator output is evaluated by a slow process at downstream network sites.

† Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225), ARPA (ONR N00014-92-J-4015), the National Science Foundation (NSF IRI-90-24877), and the Office of Naval Research (ONR N00014-91-J-4100).

‡ Supported in part by the Air Force Office of Scientific Research (AFOSR F49620-92-J-0225).