1 Vision

Learning is an active, dynamic behavior that emerges from interactions between the developing brain of a child and a social world. Until recently not enough was known about the brain to help guide educational practice. This is rapidly changing as new discoveries are made about the brain and new techniques are available for probing the learning brain. We propose to bring together a collaborative team of researchers, educators, and communicators who will bring basic science into classrooms and, conversely, use the classroom as a living laboratory to inform and guide the basic science.

Successful learning depends on timing. The brain is exquisitely sensitive to the temporal structure of sensory experience: at the millisecond time scale in the auditory system, at the second time scale in reinforcement learning, at the minute time scale for action-perception adaptation, and at the day to week time scale for consolidation and maturation. Despite the relevance of time to all aspects of learning, action, and neural coding, the temporal dynamics necessary for flexible and adaptive learning has only recently become a focus in educational settings. The integrating theme of our Science of Learning Center is temporal dynamics.

As a pervasive feature of the organization of experience at multiple scales, it is unlikely that an understanding of temporal dynamics can be gathered from a single line of inquiry. Working as an integrated network of scientists, the UCSD Dynamic Learning Center intends to move science forward through the theoretical integration of multiple lines of inquiry. Too often in science, ideas that are well-known in one field are rediscovered in another. One way to avoid this is to be interdisciplinary from the beginning. We propose to address this by creating communities of scientists that break down disciplinary and institutional barriers in pursuit of a common set of research questions. Thus, to make fundamental progress, we believe that a collaborative research model, involving interdisciplinary teams, is the only appropriate one. In pursuing our goal, we have developed research networks that combine researchers in machine learning, psychology, cognitive science, and neuroscience, molecular genetics, biophysics, mathematics, and education to focus on a single set of issues from multiple perspectives. We are explicitly not suggesting groups that meet and tell each other about their research. Rather, we are suggesting groups that synchronize their research by running parallel experiments in animals, people, and theoretical models.

The four research networks (including the sensorimotor, interacting memory systems, perceptual expertise, and social interaction networks) will progress up the temporal hierarchy from the fine scale of spike timing to the exquisite cadences of social interactions. Given the inherent challenge of spanning time scales, the four networks of researchers have chosen tractable, integrative, and convergent methods of studying the dynamics of time across learning and retention. Nested time scales ranging from milliseconds to years are critical in sculpting changes in the neural system from the efficacy of a single synapse to the alteration of synaptic weights across distributed networks. Examination of the way in which differential neural circuits are recruited as a function of time and modality of input will be examined, alongside the precise timing necessary for coordinated output of actions.

Ultimately, the goal of our center is to place the findings and questions generated by each research network in the context of a larger dynamic network of data and disciplinary perspectives. Through the marriage of computational modeling with other disciplines each network will generate computational models of the temporal dynamics of learning that are informed by a multi-disciplinary team. The existence of such formal models will generate testable hypotheses positioning experimentalists and educators to move the field of learning forward.

With the aim of diversity of thought, experience, and culture, The UCSD Dynamic Learning Center proposes to fully integrate scientists, students, educators, and corporations for the purpose of mutual discovery regarding the science of learning. Scientists will be challenged to educate teachers regarding the science of learning in an interactive forum that will be aimed towards reformation of educational practices in accordance with scientific principles. Dissemination of the findings of the Learning Center will be translated and brought to every home and classroom through The Science Network, a television and internet channel dedicated to providing public access to science.
2 Background

One of the grand challenges of the 21st century is to understand and emulate the learning capabilities of biological organisms. Normal children, for example, learn to see, to speak, to understand the language that surrounds them, to walk, and to interact felicitously with caregivers and playmates. These problems are extremely different, both in the time scales involved and in the kind of data being processed. On the other hand, reading this very sentence presents a complete different set of temporal issues. Each of these scenarios represents a problem that has been dealt with in machine learning as an issue pertaining to probabilistic inference. Surprisingly, similar Bayesian modeling issues have been applied, with some success, to each of these situations. Future success will depend largely on developing new active learning models.

Whereas numerous ingenious models of single neurons and cellular compartments have been developed, few such models bridge the gap between neuron function and cognition. More commonly, those models that attempt to address cognition are overly simplistic, failing short of neural feasibility. The current proposal sets forth the interplay of computational models and cognition, such that the predictions of models will be experimentally tested and the models will be updated based on the experimental results.

Learning occurs within a continuous temporal framework, such that it is inextricably bound to time. In studying brain learning, experience-based training and education, or social learning, time predominates as an organizing principle. Inherent in the psychobiology of time is the concept of nested time scales - in which learning processes operate. From neurobiology, the notion of spike-time dependent plasticity (STDP), where the timing of pre and post-synaptic spikes must be within a certain number of milliseconds of each other, and the efficacy of the synapse is enhanced (depressed) if the pre- synaptic spike precedes (follows) the post-synaptic spike, suggests a method by which neurons might encode causal relations about the world around them. Rao and Sejnowski suggest a particularly concrete link between the temporal-difference (TD) learning rule used in modern Reinforcement Learning, and STDP [1]. Using a biophysically detailed model neuron, showed that the equations for the apparently differing learning rules were in fact, identical under certain assumptions. This suggests that deep within the brain, one of the most powerful learning rules known in Artificial Intelligence is embedded in our synapses. This has remarkable relevance to cognitive neuroscience, as this means that STDP is likely to underlie a form of learning in cortical and hippocampal systems that is predictive rather than correlational.

This is just one example of the power of studying learning within a temporal framework, in that dynamics occurring at a very early time scale may have enormous implications for aspects of learning that are most often recognized at a much broader time scale.

An example of embedding this kind of technology, created by members of our social interaction network, RUBI the educational robot is likely to be a landmark prototype for the future implementation of robots in an educational setting. A real time information maximization (InfoMax) controller was implemented in RUBI, to detect people using computer vision and contingency information. The system worked robustly requiring little bandwidth and computational cost. This suggests that contingency information is indeed a reliable source of information to detect the presence of humans, as well as to engage in real-time learning. It is likely that the infant brain is able to capitalize on this source of information as well. Rubi currently attends the Early Childhood Education Center on a daily basis. She has been embraced by her human preschool cohort.

A large scale educational outreach plan will allow us to incorporate students at every level of education in our research and outreach. A variety of programs aimed towards the advancement of underrepresented minorities in science have been put in place, with a respect for the creativity that is likely to arise from a future of diverse scientists. For those who choose not to pursue science, the training will still contribute towards rectifying the math and science educational gap in America. National workshops and classes for teachers and administrators will make cutting-edge research available for the purpose of updating educational practices to reflect our new knowledge of the temporal dynamics of learning. Finally, we will partner with a non-profit television production company, The Science Network, will make our research available to a broad sector of the population.
3 Research Plan and Strategy

3.1 Introduction: The Network Approach to Research

Our model for collaboration is the Perceptual Expertise Network (PEN), a group of ten investigators (Marlene Behrmann, Dan Bub, Gary Cottrell, Tim Curran, Isabel Gauthier, Tom Palmeri, Bob Shultz, David Sheinberg, Jim Tanaka and Mike Tarr), numerous students and shared postdocs. PEN has been investigating the question of the neurobiological, behavioral, and computational underpinnings of perceptual expertise, which can be glossed as the ability to rapidly categorize an object from a group of similar objects at the level of the individual. In this view, we are all face experts, but faces are not special, they are simply the most well-known example of perceptual expertise.

Several features of PEN make it a novel paradigm for research. Key among these is that member scientists do not simply exchange ideas and insights about perceptual expertise but work collaboratively together to answer fundamental questions. The scientists involved study normal human subjects, subjects with acquired and developmental brain abnormalities, monkeys, and computational models of visual cognition. The methodologies used include single and multi-electrode recordings, fMRI, ERP’s, behavioral studies, training studies, neural networks, and abstract models. The group meets several times a year as a whole to discuss research directions, and hash out new experimental designs and stimuli that can be applied with little or no change to monkeys, human subjects, and neural networks, allowing comparative research. The number of collaborative projects between labs has grown from 3 before PEN started to over 25 in just five years (see Figure 1, Left). Over 30 collaborative papers have been produced, with many more influenced by our collaborations.

The UCSD Dynamic Learning Center will be composed of four such networks, including PEN, all focused on the issue of the temporal dynamics of learning (see Figure 2). Indeed, the vision for this Center is a network of networks model. While the four networks focus on different aspects of this issue, there are cross-cutting themes: the role of timing in learning and activating representations, the fine-grained analysis of temporal processing using multiple techniques, and the central role of computational models in understanding the mechanisms of learning. Each network will have semi-annual workshops in order to maintain close ties between labs and to quickly learn each other’s vocabularies. We also plan to have a yearly workshop where all networks come together to share our findings, and synchronize the networks to a set of shared concepts, paradigms, and issues.

The four networks are: Sensorimotor Learning, Interactive Memory Systems, Perceptual Expertise, and Social Interaction. In addition, our project will include cross-cutting resources that will be available to all four networks: The Education/Outreach Center, The Spatio-Temporal Brain Dynamics Facility, The Data Sharing Facility, and The Motion Capture Facility. The relationship between these is shown in Figure 2. As is shown in the figure, each Network and the Education/Outreach Centers are headed by
co-PI’s on this grant (Palmeri and Gauthier are co-PI’s on the PEN subcontract). Paula Tallal and Terry Sejnowski will jointly direct the Education/Outreach Center, which is described in Section 4. We expect our networks to grow in a manner similar to PEN, as shown in Figure 1, with new synergies emerging from inter-network collaborations. Indeed, many of our investigators are in multiple networks, which will facilitate cross-network fertilization. The cross-cutting facilities will also encourage interactions between the networks, in particular, the Data Sharing Center, which will allow us to share a variety of multi-modal and multi-time-scale data.

Here we outline the new efforts that will be made possible by a Center-level grant. There are seeds of some of these efforts already in existence, but coordinating these under the Center model will create a new level of synchrony between them, and in many cases, the projects would not be possible at all without a Center to support them. We first describe the four networks and then the cross-cutting resources.

3.2 The Sensorimotor Learning Network

Sensorimotor Network Overview

Humans learn in many different sensory and motor modalities, from learning to recognize speech and printed words (which involves auditory and visual recognition) to learning to walk or speak (which involves learned movements of limbs and vocal musculature). However, all forms of real-world learning are ultimately sensorimotor in that they involve both sensory and motor components. For example, speaking requires not only learning appropriate vocal motor control, but also learning to interpret ongoing auditory feedback to correct motor errors. Both sensory and motor aspects of learning have strong temporal dynamics, from the millisecond time scale (timing of stimuli and neural spike patterns required to drive learning) to minutes (training duration required to drive learning) to months and years (duration of long-term memory).

In the Sensorimotor Network, we bring together the study of sensory learning in sensory areas of the cerebral cortex and motor learning of limb and hand movements, to study similarities and differences among multiple learning mechanisms that operate on different timescales. The sensory learning component will characterize the precise temporal features of synapse-level biological learning rules ("STDP rules"), and
determine how these rules generate precise timing requirements for sensory perceptual learning. The motor component will focus on human motor learning, and specifically on two forms of motor learning with very different temporal scales, to characterize the learning mechanisms that guide them. Understanding the temporal features of learning in these different systems will allow us to develop a common framework for sensorimotor learning.

3.2.1 Spike-Time Dependent Plasticity

Overview This project will investigate the temporal features of synapse-level biological learning rules, and determine how these features generate precise timing requirements for behavioral learning in animals and humans. Historically, cellular studies of information storage have focused on "Hebbian" synaptic plasticity mechanisms in which coincident pre- and postsynaptic action potentials (spikes) cause rapid, persistent changes in synaptic strength [2]. Recent findings have significantly revised this model by demonstrating a strong temporal component to these learning rules: when presynaptic spikes lead postsynaptic spikes by 0 to 20 ms, synaptic strength increases, and when postsynaptic spikes lead presynaptic spikes by up to 100 ms, synaptic strength decreases. This “spike timing-dependent plasticity” (STDP) has been documented at more than a dozen different synapses in the brain, and has stimulated much interest among experimentalists and theorists [3, 4]. In a second temporal feature of synaptic plasticity, temporal clustering of neural activity over seconds to minutes ("spaced" vs. "massed" training) determines how long synaptic plasticity persists. Thus, temporal features of neural stimuli from milliseconds (STDP) to minutes (spaced vs. massed training) affect information storage at the synaptic level. These discoveries open up new avenues for understanding the many forms of information coding, circuit-level plasticity, and behavioral learning (including human language learning) that depend on the precise timing of neural spikes or behavioral stimuli [5].

In the projects proposed below, we will characterize STDP at different synapses and investigate how they contribute to training-induced changes in sensory receptive fields and sensory perceptual learning in animals and humans. Experimental learning paradigms will include visual perceptual learning in cats and humans, which shares the precise timing requirements of STDP, auditory and visual sequence learning in rats and humans, which is critically involved in learning of language, speech and reading, and reinforcement learning, in which precise timing of reinforcement is critical for optimal learning. Each project will have, in addition to a physiological and behavioral component, a modeling component whose goal is to provide a framework for understanding how STDP and related processes give rise to learning at the behavioral level. The ultimate goal is to better integrate our understanding of STDP and other temporal features of synaptic plasticity across multiple levels of analysis, and specifically to understand how STDP mediates timing-sensitive forms of learning, in order to improve learning paradigms for normal and learning-impaired children.

Research Team The investigators for this project have strong track records in studying STDP and temporally dependent behavioral learning: Mu-Ming Poo and Dan Feldman have studied the mechanisms and properties of STDP in slice preparations and in vivo. Yang Dan has shown that training with precisely timed visual stimuli alters visual representations and visual perception according to STDP learning rules. Paula Tallal has studied auditory and visual sequence learning in humans, and has designed interactive computerized training “games” that improve the ability of children to make fast temporal discriminations, and significantly improves reading and learning. Terrence Sejnowski, Paul Munro, Tony Bell, and Michael Mozer have performed computational and theoretical studies of STDP and its consequences in neural networks, and shown how STDP changes the ability of networks to detect temporal patterns and to predict subsequent inputs.

Specific Projects 1. Are STDP learning rules and other temporal features of plasticity specialized across different synapses and brain areas, and does this cause differences in temporal requirements for learning across sensory modalities? To address this, we will compare STDP rules in rat brain slices across different excitatory and inhibitory synapses in somatosensory, visual, and auditory areas, and measure the timing
requirements for rat behavioral perceptual learning in these modalities. In modeling studies, we will implement the observed STDP rules in realistic cortical network models of each brain area, to predict the temporal requirements for circuit-level plasticity. This work will establish whether discrete classes of STDP rules exist and will help define more fully the range of time scales over which STDP rules and temporal-based learning function. Based at UCSD. Investigators: Feldman, Sejnowski, Bell, Tallal.

2. How do natural sensory stimuli and appropriate behavioral reinforcement trigger STDP, sensory receptive field plasticity, and behavioral learning? Natural stimuli pose unique problems for STDP due to the complexity of the spike trains they elicit. Preliminary data show that learning of natural stimulus sequences can be detected physiologically in rat and cat visual cortex, and here we propose to test, using physiological and modeling techniques, whether and how this involves STDP. The timing of behavioral reinforcement is also critical for learning, but the precise timing requirements for reinforcement of sequence and language learning are not known. We propose to study the effects of different temporal reinforcement schedules on the precision of learning novel verbal and non-verbal temporal patterns relevant to speech and language, and to use modeling to relate these schedules to STDP and other synapse-level learning rules. Based at UC Berkeley. Dan, Tallal, Munro.

3. What is the effect of neuromodulation on STDP, and does this have instructional or clinical relevance in children and aging adults? Neuromodulators associated with attention and arousal (for example, acetylcholine, ACh) are key regulators of learning and training-induced receptive field plasticity in sensory cortex [6]. Recent findings suggest that neuromodulators may regulate learning by altering STDP learning rules at the cellular level [7]. To study this, we will enhance or suppress specific neuromodulators with pharmacological and genetic techniques, and assess the effect on STDP and on sensory perceptual learning and auditory sequence learning in animals. This experiment may suggest treatment strategies to enhance learning in humans. Based at UCSD. Feldman, Sejnowski, Bell, Tallal.

4. What are the detailed biophysical effects of STDP on single neurons, and how do these lead to specific modes of information processing and learning? In addition to altering synaptic strength, STDP can modulate neuronal excitability, dendritic integration, and dynamical properties of synapses [3]. We will investigate these effects in hippocampal cultures and cortical slices, and use modeling to predict their consequences for information storage, computation, and learning. Predictions will be tested experimentally by using STDP-based training protocols to train single neurons on different computation, recognition, and categorization tasks. Based at UC Berkeley. Investigators: Poo, Dan, Mozer, Munro.

Together, these studies will determine the precise temporal requirements for synaptic plasticity and information storage in neural networks, and will elucidate how temporal features of synaptic plasticity (including STDP) determine the temporal requirements for behavioral learning on the milliseconds to seconds time scale. Though experiments will be performed using animal models of learning, they are directly relevant to many forms of learning in humans, including sensory perceptual learning and language learning [5, 3]. This project is closely connected to the Motor Learning and Temporal Lobe projects, which involve forms of learning that are likely to share similar underlying mechanisms. Our behavioral studies of learning in different modality are also highly relevant to the Multimodal Learning project. It is our hope that this project will suggest novel strategies to improve learning performance in normal and learning-impaired people, which will be developed by the Education/Outreach Center.

3.2.2 Motor learning across timescales: from adaptation to skill acquisition

Overview This project will combine psychophysical and theoretical work on human motor learning, with the goal of understanding the commonalities and differences among multiple learning mechanisms that operate on different timescales. At one end of the timescale continuum we have sensorimotor adaptation: when subjects perform a familiar task in the presence of mechanical or visual perturbations [8, 9, 10], they form an internal model of the modified environment and use it to cancel the perturbation [11, 12]. Adaptation takes place within a single experimental session, sometimes within a few trials. At the other end of the continuum we have acquisition of new motor skills [13, 14] - which involve formation of a new control strategy rather than adjustment of an existing one, and typically require an amount of practice that is orders of magnitude larger. While both processes are labeled “motor learning” in their corresponding literature, it
is not presently clear what they have in common. Here we propose to study the continuum of motor learning mechanisms in a unified way, by designing novel tasks that span a range of difficulty levels, and modeling the behavioral changes observed in the course of learning within the optimal control framework. The same paradigm will be applied to both normal subjects and patients with Parkinson's disease.

**Research Team**  The core team will consist of Emanuel Todorov and Howard Poizner, who have worked on a range of topics relevant to this proposal: training and rehabilitation in virtual environments [15, 16, 17, 18], theories of sensorimotor function based on optimal control [19, 20, 21, 22], iterative learning algorithms for control of complex dynamics [23, 24, 25], sensorimotor adaptation and control and their failure due to loss of specific sensory or motor neural systems [26, 27, 28, 29, 30, 31, 32, 33, 34]. The team will collaborate with Terrence Sejnowski, who has extensive experience in applying Reinforcement Learning to Neuroscience.

**Specific Projects**  1. We will design two families of psychophysical learning tasks that both span a wide range of difficulty levels. Different difficulty levels are likely to require different amounts of practice, evoking learning mechanisms that operate on different timescales. The first family involves reaching and obstacle-avoidance arm movements in 3D. The subject’s arm will be tracked in real time, the instantaneous joint angles will be estimated, and the arm will be rendered in a 3D Virtual Environment. The displayed arm kinematics will differ from the true kinematics. Subjects will have to learn to control the displayed arm in order to accomplish a specified virtual task. This setup will allow us to explore a rich set of kinematic changes, from simple scaling of arm segments (easy) to swapping the motion of elbow and shoulder joints (hard). The second family of tasks will involve hand movements, whose goal is to control a simulated marionette moving in a simulated 3D environment. Learning to control a realistic marionette can be very hard, but we can also simulate arbitrarily simple “marionettes” - such as a point mass attached with a string to one of the fingertips. Hand manipulation is a fascinating yet under-explored subject, and we are looking forward to studying it systematically.

2. We will model learning across timescales within the unifying framework of optimal control theory. Optimality models have been very successful in explaining features of skilled performance [35], but have not systematically addressed the issue of how the motor system comes to behave optimally. The answer clearly has to do with learning. Indeed, there exist a number of computational learning methods [36, 37, 38] that can approximate the optimal controller - methods which we will adapt to our specific tasks. We will seek to model not only the behavior after learning, but the entire time course of behavioral changes along with any qualitative phases that we manage to identify. Adaptation will be modeled as re- optimization of an already existing control strategy applied in a perturbed environment. Skill acquisition will be modeled as “tabula rasa” optimization that does not assume a preexisting structure. Existing computational methods for approximately optimal control (especially those in Reinforcement Learning) tend to be slow and require large amounts of data. This may be fine as a model of skill acquisition, but seems inconsistent with humans’ ability to adapt in a few trials. To resolve that problem we will develop new model-based re- optimization methods, that utilize all the information present in a perturbed movement trajectory and not just the scalar reward signal obtained at the end.

3. We will seek to understand motor learning across timescales by studying the way in which it fails in patients with Parkinson’s disease, and the way in which it is (or is not) reinstated by dopamine replacement. Parkinson’s patients are of specific interest here because they have a primary basal ganglia lesion of dopamine cells (which are known to encode reward-related information [39]). It will be interesting to compare the motor learning deficits observed in patients to the deficits of Reinforcement Learning algorithms that have been given inaccurate or insufficient reward information.

**3.3 The Interacting Memory Systems Network**

**Multiple Interactive Memory Systems Overview**

The extent to which different neural circuits are engaged during learning, as well as the extent to which behavioral expression is dependent on processing within a particular neural circuit remain critical issues in
understanding the neural basis of learning and memory. Gaining such an understanding will heavily rely on assimilating knowledge regarding the temporal properties of information presentation, reinforcement contingencies, and behavioral demands that differentially engage and promote processing by constituent neural circuits. An understanding of these dynamic systems will serve to consummate the goal of providing a new foundation of brain-based learning from which educators can grasp how to utilize the capacities and liabilities of the neural system to optimize learning and retention of particular types of information, reduce the memory load brought about by learning, and to enhance flexible and conscious access to this knowledge base.

Thus, two distinct collections of projects aim to explicate the intricacies of timing within, across, and between multiple neural circuits subserving learning and memory. The primary goal of the first set of projects is to behaviorally and computationally explicate the temporal learning parameters underlying optimal long-term retention. The primary goal of the second set of projects is to elucidate the temporal and environmental parameters that engage the coordinated activity of distinct neural networks underlying learning and memory and, subsequently, allow a particular neural network to prevail in mediating behavioral expression.

3.3.1 Optimizing Memory Retention: Experimental and Computational Studies

Overview Educational failure often arises not because a learner fails to grasp important concepts and information, but rather because his or her mastery of the information is tenuous and rapidly lost over time. Many studies have shown that students have extremely poor recall of material in courses that they did well in several years earlier [40], and teachers often notice the dramatic forgetting which takes place over even a summer vacation [41]. Forgetting is a temporal process, and as such, it is not surprising that the temporal characteristics of learning also play into forgetting. Every introductory psychology student learns about the spacing effect, the finding that spaced practice aids retention over massed practice. Appropriate practice of material can lead to retention improvements of 30%, but the detailed nature of the spacing effect is not as simple as is taught in Introductory Psychology. Cepeda, Pashler, Coburn, Wixted, Rohrer, and Mozer (under review) have identified a complex interaction between the spacing of practice and the duration of optimal retention. If material is to be retained for only seconds, then massing study is superior to spaced study. A very different profile of optimal spacing of material is observed if the material is to be retained for months or years.

Specific Projects Hal Pashler (UCSD Psychology) and Michael C. Mozer (University of Colorado, Computer Science) have an ongoing collaboration on the temporal factors that promote durable learning and on the neurocomputational basis for such effects. The proposed research involves expanding this collaboration to examine concrete procedural variables that can reduce the rate or extent of forgetting. A developmental component will be added to this project by Gedeon Deak (UCSD Cognitive Science and Teacher Education Program), an expert in children’s word and fact learning and concept formation (Deak & Gendreau, in review). This component will examine spacing effects in four to seven year old children, informing us about developmental changes in the systems underlying timing effects in learning. Thus, the collaborative experimental effort proposes to illuminate systematic changes in the temporal parameters of learning for long-term remembering, across a wide span of development. With Mozer’s computational expertise, the group is pursuing a computational analysis of these phenomena, to help explicate the neurocomputational underpinnings of memory. The work focuses on three empirical phenomena relating to memory and its loss:

(a) THE SPACING EFFECT: When an individual has multiple opportunities to study an item, long-term memory retention is sometimes improved, and forgetting attenuated, when the temporal distribution of study experiences is greater.

Spacing of study will be manipulated in different experimental and computation settings, so the best distribution of study experience is illuminated.

(b) BENEFITS OF TESTING DURING STUDY: After a learner has started to master new material, testing with feedback often produces better and more durable learning than just re-studying the same material (e.g., [43]). While testing is commonly regarded in education as just a means of assessment, growing
A variety of different forms of testing during learning will be compared.

(c) FORGETTING CURVES: As the retention interval between study and test is increased, performance drops; the function is better characterized by a power function rather than an exponential decay. Forgetting rate will be examined as a function of retention in each of the above conditions.

Over the past several years, with support from the Institute of Education Sciences (US Dept of Education), Pashler’s lab has been examining the role of spacing and testing in modulating the rate of forgetting [45, 45, 46]. While it has long been known that spacing can be beneficial to learning, the boundaries of the effect have not been clear, and little translation to practical application has occurred. One major reason for this is because the literature has focused almost entirely on very short retention intervals of one day or less. Thus, it has not been clear how long an inter-study spacing is required to promote long-term retention over practically important time periods.

A large-scale internet testing system has been developed in the Pashler lab, a system that tests thousands of subjects in multiple experiments over periods up to a year or more, in domains ranging from learning novel facts and foreign language vocabulary to visuospatial pattern learning. The results currently being collected are beginning to provide a quantitative handle on the nature of spacing effects and their interaction with retention interval (Cepeda et al., under review ). The current proposal will take a step further in modifying this testing system for use across stages of development.

Using the first results from this system, Mozer and Pashler have developed individual models of various phenomena relating to fact learning [48]. Currently, they propose to integrate these models in a unified, quantitative, neurocomputational model of fact learning (including spacing, testing, forgetting). The unified model will focus on how temporal and qualitative aspects of study affect memory assessed at different times. Beyond the scientific value of this unified model, their goal is to use the model in designing individualized instructional programs in classrooms and computer-aided instructional software. For fact learning, an instructional program specifies, based on previous training and feedback from the learner, which item should be studied next, for what duration, and whether the learner should be tested on the item, in order to optimize recall over the times in the future when the information will be required. The essential idea is to use the model to predict human performance, feeding the model alternative study programs, and then choosing the program that yields optimal performance. Rather than a trial-and-error simulation approach, optimization can be achieved via standard machine learning techniques such as gradient ascent or expectation maximization.

The unifying modeling technique Mozer and Pashler will explore is the temporal difference framework of Sutton (1988). Temporal difference learning provides an efficient learning method for anticipating the future in an uncertain environment. Temporal difference methods are generally applied over a single time scale, but the hypothesis of Mozer and Pashler is that the same technique at multiple time scales will prove useful in integrating various phenomena of fact learning. For example, Mozer et al. (2004) used a temporal difference framework to understand the benefits of testing. Using an associative neural network model with leaky-integrator neurons and prediction via supervised temporal difference learning, they showed a natural improvement in performance with self testing, as well as other more subtle phenomena involving self testing, such as how the benefit varies with the amount of prior study. On a much longer time scale, Cepeda et al. (submitted) have shown that temporal-difference learning in an environment in which context varies according to a random walk can explain the highly nonlinear relationship between spacing and optimal retention interval. Key to the integration of various phenomena is the combined modeling of both fine-grain temporal dynamics of information propagation within a trial [49] and coarse-grain trial-to-trial learning dynamics.

The results of the experimental and computational work will provide a comprehensive view of the role of temporal variables and testing procedures in improving long-term retention. Also, the results will address differences in the most beneficial factors for different age groups. By developing a formal model of these factors, the group will be able to make predictions and recommendations for improved educational practices, with a goal of promoting long-term learning and educational success. Based at UCSD. Investigators: Hal Pashler, Mike Mosher, Gedeon Deak.
3.3.2 The Dynamics of Learning and Memory Networks: Temporal Lobe Learning

Overview  The interplay of two distinct theoretical systems of learning and memory, the “declarative memory system”, proposed to support conscious memory of facts and episodes and the “habit system”, proposed to support gradual, incremental learning of associations, will be investigated as a model of dynamic interactions across seemingly disparate learning and memory systems [50]. From a neural perspective, the medial temporal lobe system is essential for declarative memory function, whereas the basal ganglia or striatal system is essential for the formation of habits or gradual learning of associations. An interdisciplinary team will take a multi-level approach to the temporal and environmental parameters that engage processing by these neural networks and allow a particular neural network to prevail in mediating behavioral expression.

Research Team  The composition of this team was designed to include experts across several different domains of learning, such that the divergent theoretical views and experimental approaches provide a stage from which knowledge can be accelerated. Randy OReilly, Janet Wiles, and Jeff Elman each have substantial expertise in developing behaviorally and/or neurally feasible computational architectures that have furthered understanding of network dynamics underlying learning. Larry Squire was premier in identifying explicating these different systems of learning and memory in the brain. Robert Clark and Andrea Chiba are young investigators who hold expertise in establishing the functional role of the hippocampus in declarative and temporal learning, respectively. Fred Gage discovered neurogenesis in the adult hippocampus. The proposed projects of this team of investigators will fuel a multi-dimensional approach to the temporal dynamics of learning and the functional relevance of different neural circuits across this temporal landscape. Paula Tallal is a leading expert in language learning, educational remediation of language and reading disabilities, and temporal sequence learning. She is co-founder of the Scientific Learning Corporation.

Specific Projects  1. What are the temporal and functional dynamics of neural networks underlying the initial learning of a discrete set of events, leading to the compression of these events as a “habit”? Specifically, this project will address the inherent computational properties of neural structures that preferentially lead to rapid learning (the putative hippocampus) relative to those found in systems that acquire general statistical information about the environment that emerge on a slower time scale (interactions between putative cortex and putative basal ganglia). From a model of such functional anatomy, predictions will be set forth regarding the computational properties of actual neurons in the above structures across different stages of learning. Such predictions will be tested in a rodent model of sequence learning [51]. Local firing properties of the hippocampus, posterior cingulate cortex, anterior cingulate cortex, and basal ganglia will be acquired from the brains of rats undergoing learning and gaining expertise on a cued sequence learning task [52]. Subsequent to data collection, the computational tradeoffs allowing a particular neural structure to prevail during a given stage of learning will be analyzed. Investigators: Andrea Chiba, Randy O’Reilly, Paula Tallal

2. What are the temporal contingencies between stimuli that engage different neural systems (hippocampus, basal ganglia, cerebellum)? What is the relevance of awareness to learning in these systems? What are the specific roles of different hippocampal subregions (CA1, CA3, Dentate Gyrus) in learning? Parallel investigations of humans (imaging studies) and rodents (multi-site electrophysiological recording) will be undertaken in order to investigate the temporal parameters under which different neural populations are engaged during distinct forms (trace and delay) of conditioned learning [53]. These forms of conditioning rely on dissociable neural architectures, such that the hippocampus preferentially codes trace conditioning (500 ms or more between stimuli) and the cerebellum preferentially codes delay conditioning (100 ms or less between stimuli). The dynamics between these neural architectures across learning has not been investigated. It is likely that both the hippocampus and cerebellum are engaged during delay conditioning, but that the cerebellum has control of behavior at this time point. Likewise, it is likely that each the cerebellum and the hippocampus are engaged during trace conditioning. Here, not only does the hippocampus have behavioral control, but it is likely sending reformatted information to the cerebellum in the temporally overlapping fashion that the cerebellum can use. Such predictions will be experimentally investigated in an animal model of learning.
During delay conditioning trials the firing properties and local field potentials of neurons in the hippocampus, cerebellum, and the pontine nuclei (the putative interface between the hippocampus and cerebellum) will be characterized. Behavioral parameters will then be changed to trace conditioning and the firing properties of the three structures will be compared to those that exist during delay conditioning. Computational analyses of the temporal dynamics of these structures across learning epochs will elucidate the network properties underlying temporally contingent learning. Investigators: Robert Clark, Larry Squire, and Andrea Chiba

3. What is the nature of neurogenesis in the dentate gyrus of the hippocampus? What is the functional role of these new neurons in forming new memories? Computational models of neurogenesis in the dentate gyrus will be used to resolve the temporal problem of the slow maturation process of new neurons with the rapid dynamical response of the dentate gyrus circuit. The functional significance of dentate gyrus processing to memory formation will be considered on two different time scales, such that the initial transient response of the dentate gyrus is predicted to signal novel events, and the longer term function is proposed to make each event distinct from other events [54]. Complex systems analyses will be applied and subsequent predictions will be made regarding the functional role of new neurons in the hippocampal system. Subsequently, neurogenesis can be manipulated in different behavioral paradigms to test these predictions. Investigators: Janet Wiles, Jeffrey Elman, Rusty Gage

4. In order to facilitate knowledge transfer amongst laboratories all post-doctoral researchers on this project will be centered at UCSD and will spend a percentage of their time in the associated off-site laboratories for training. All team members will meet regularly to integrate the resultant behavioral data and the computational predictions, in order to set forth an integrative theoretical and computational framework of the temporal dynamics of learning and plasticity engaging medial temporal lobe function and the computational advantages mediating the fluid transitions between declarative and habit systems in ecologically valid behavioral settings. Investigators: Andrea Chiba, Robert Clark, Jeffrey Elman, Rusty Gage, Randy O’Reilly, Larry Squire, Janet Wiles, Paula Tallal

3.4 The Perceptual Expertise Network

Perceptual Expertise Network Overview

Radiologists, ornithologists, firefighters, and other specialists are noted for their remarkable ability to rapidly recognize, categorize, and identify objects and events in their domain of expertise. Understanding the unique abilities of experts can certainly have important real-world implications for enhancing the development of expertise in the workplace. However, understanding perceptual expertise is more than characterizing the behavior of individuals with idiosyncratic skills in highly specialized domains. Perceptual expertise may also explain some of the unique aspects of recognizing such things as faces [55, 56, 57], words [58], or letters [58]. Viewing perceptual expertise as the endpoint of the normal trajectory of learning, rather than an idiosyncratic skill, allows us to exploit studies of experts to understand the general principles and limits of human learning and plasticity. Viewing faces, words, and letters as domains of perceptual expertise can yield new insights into how ravages of brain damage might lead to the perceptual and cognitive deficits seen in autism, dyslexia, agnosia, and other conditions, and can lead to breakthroughs in education and treatment.

We will explore recognition, categorization, and multimodal interactions by investigating adult novices and experts, individuals with agnosia, dyslexia, autism, and non-human primates. We will employ computer models to probe the computations underlying performance in these experimental paradigms. Our broad scientific goals focus on (i) unraveling the fine-grained temporal dynamics of expert perception and recognition, (ii) examining the temporal dynamics of multimodal interactions that so characterize real-world learning experiences, and (iii) understanding the interactions of dynamics at different temporal scales throughout the development of expertise.

Research Team The Perceptual Expertise Network (PEN) was established four years ago through a grant from the McDonnell Foundation as part of its “Bridging Brain, Mind, and Behavior” program that supports interdisciplinary research in the neurobiological, cognitive and behavioral sciences. PEN is currently comprised of 10 investigators and their graduate students and postdoctoral fellows from seven universities in the
United States and Canada. PEN members study object recognition, categorization, and expertise from a variety of perspectives. Isabel Gauthier and Michael Tarr have investigated the behavioral and neural changes that take place with expertise. Jim Tanaka has conducted important behavioral studies of expertise and face recognition. He and Tim Curran have used ERP measurements to study temporal changes in brain dynamics with expertise. Daniel Bub and Marlene Behrmann have characterized the behavioral deficits in prosopagnosia and other brain disorders that some have characterized as failures of expertise. Robert Schultz has used an expertise framework to understand deficits in face recognition and other tasks in autism. David Sheinberg has examined changes in single unit neurophysiology in awake behaving monkeys developing expertise in tasks similar to those performed by human subjects. Thomas Palmeri has developed stochastic computational models of categorization and expertise from a cognitive modeling tradition. Garrison Cottrell has developed computational models of object recognition and categorization from a machine learning and neural networks tradition. Over the past four years, a growing web of collaborations has developed within the group. The result is that PEN members are no longer restricted by the methods and techniques they know best, but can answer important questions using the panoply of tools represented in the expertise of PEN.

In this grant, the original PEN team is networked with five additional scientists to further expand the tools and expertise base. Paula Tallal has developed training paradigms for improving auditory temporal processing in language impaired children and shown that this significantly improves reading in these children. Scott Makeig and Marty Sereno are experts in their respective fields of EEG and fMRI analysis. Marty Sereno uses innovative presentation paradigms to discover new higher order visual and multimodal areas in humans. Scott Makeig is revolutionizing EEG analysis. Jochen Triesch and Virginia de Sa have both worked on machine learning algorithms that learn from inputs in different sensory modalities. They have also both worked on computational neuroscience models of synaptic learning involving homeostatic plasticity.

3.4.1 Unraveling The Temporal Dynamics of Perceptual Expertise

Overview Experts are fast. They make fine perceptual discriminations and precise identifications with speeds that can astonish the novice observer. What makes an expert so fast? Have they developed qualitatively different ways of processing information over time? Have they created new ways of representing information? Or have they discovered optimal ways of using or enhancing the representations they had as novices [59, 60]? Or is it some combination of these? Unfortunately, too little is known about how experience shapes the moment-to-moment temporal dynamics of a perceptual decision.

Unraveling these changes in temporal dynamics demands a coordinated multi-pronged research strategy. We use experimental techniques to systematically probe how knowledge is used over time, how perceptual information is integrated over time, and how decisions evolve over time. We relate temporal dynamics of perceptual decisions with temporal dynamics of neural activity revealed by signature ERPs in conjunction with fMRI. In collaboration with the Human Brain Dynamics group, we also will apply single-trial EEG analyses to more thoroughly examine online changes in brain dynamics associated with expertise. We relate this human data to the temporal dynamics of behavior and individual neuron activity in awake behaving monkeys. We examine how brain damage influences the temporal dynamics of perceptual decisions, both to better understand the effects of brain damage itself and to help reveal the direct causal role of those brain areas in undamaged brains. And we incorporate temporal dynamics into the next generation of computational models of behavior and neural activity.

Specific Projects 1. The Dynamics of Expert Perception and Representation. Complex objects, whether natural kinds or artifacts, are composed of multiple parts or features that can be organized in various ways, often with subtle variations yielding important differences. The best example is the human face, whose features are made of eyes, noses, and mouths of slightly different shapes that are arranged in subtly different configurations. But componential and configural properties are also found in letters, words and non-face images. One way of characterizing of experts is that they see the whole before the parts. Indeed, there is evidence that experts are more sensitive to the holistic properties of an object. But does the holistic
representation of the expert imply that these objects of expertise are not also decomposed into individual components?

Temporal dynamics are key for understanding the nature of holistic representation in at least two respects. First, the whole may be seen before the parts. We will conduct experiments where we systematically control the time allotted for a response. If experts automatically invoke holistic representations, then holistic effects could emerge early in the time-course of responding. But if holistic effects emerge from late-evolving representations, then holistic effects could emerge relatively late in processing. Second, all components of an object may be processed in parallel [61]. We will manipulate the temporal synchrony with which aspects of an object are presented over time. Holistic representations should be especially sensitive to synchronous onset of object parts or spatial frequencies, with asynchrony disrupting holistic effects. The effects of synchrony on neural markers will be measured by modulations in ERPs and fMRI. We also plan to compare the time-course of integration for different populations. For example, one extreme form of dyslexia, called letter-by-letter reading has been framed as just that temporally sequential letter-by-letter reading. But recent work has instead suggested that while letter-by-letter readers are indeed slower, they engage parallel processing much to the same extent as normal readers [62].

2. The Dynamics of Expert Categorization. Experts categorize objects at a fine-grained, subordinate-level as quickly as they categorize objects at a more basic level. The changing temporal dynamics of expert categorization has been characterized as a qualitative shift in the entry level into conceptual knowledge. But is it really a qualitative shift from perceiving at a basic level to a subordinate level, or a quantitative shift from inefficient to efficient subordinate categorization? The very nature of the experts speeded responses pose distinct experimental challenges to unraveling their temporal dynamics. In order to overcome these temporal limitations, we will effectively slow down the time for experts to make their decisions using sophisticated object degradation techniques. Specifically, we will employ the Random Image Structure Evolution (RISE) method [63] to disrupt image coherence while preserving its low-level properties (e.g. luminance, frequency spectrum) (see Figure 3). A strength of the RISE method is that it permits degradation of the image at specified locations and selected spatial frequencies. It also allows for these components to come into view at different times, making it possible to test specific hypotheses about the time course of temporal integration over different parts of an image. These techniques will enable us to relate the time courses of expert behaviors and of neurophysiological functions as measured by ERPs. For example, we often observe expertise effects in ERP amplitude rather than latency, indicating that expertise does not merely cause existing mechanisms to work faster [64, 65, 66, 67], but perhaps instead more efficiently.

3. Can Expert Dynamics Produce Expert Performance? Perhaps experts select the right information at the right time. If so, it could be possible to improve novice performance by yoking novices to the temporal dynamics of experts. Finding performance improvements by yoking expert dynamics would suggest ways of enhancing expertise training and could inform interventions aimed at overcoming deficits of expertise seen in autism and other cognitive disorders.

As a specific example, we might explicitly control the eye movements of novices using gaze-contingent stimulus presentation in an eye tracker yoked to expert sequences of eye movements over time. If expert eye movements promote expert performance, we would expect to see better performance for novices when fixations are placed on locations preferred by experts. To really understand the dynamics of expert eye movements, models are essential. Are expert eye movements optimal? If so, in what sense of “optimal?”
most current models of eye movements are stimulus driven [68], but it is well known that visual routines
vary with the task [69]. We have been developing computational models that learn to sample from a stimulus
as they learn to categorize it. They thus optimize their eye movements based on the category structure. One
model is Bayesian, and samples according to the information theoretic notion of *information gain* [70,
71]. The second model uses reinforcement learning (temporal difference learning) to find an optimal scan
path [72]. Both of the models account for aspects of the identical task used with human subjects [73]
learning the Shepard categories. We will apply these models to the Greeble learning task, as well as to
other experiments proposed here, and compare them with the changes in eye movements of human subjects
learning the same task. The goal is to first find and then refine the best model, and use it to make predictions
on novel category learning tasks that can then be tested in human subjects.

As another example of yoking novices to the temporal dynamics of experts, we can (using the previously
describe RISE method) manipulate the spatial frequency information contained at particular locations over
time to test if the frequencies preferred by experts produce better or faster performance in novices. Moreover,
we can compare ERP and fMRI signals when novices attend to the same stimulus properties as experts at
the same time. One intriguing possibility is that feeding back matching expert neurodynamics rather than expert
decisions per se may enhance the development of expertise. This is similar to the effects of biofeedback
explored in studies led by Makeig and colleagues in the Human Brain Dynamics section of this proposal.

3.4.2 The Dynamics of Multi-Modal Interactions

**Overview** Much of the research on expert recognition has focused on visual processing, with an emphasis
on visual shape [74, 75, 76]. However, recognition is subject to multiple sources of influence, including mul-
tisensory inputs, prior conceptual knowledge, and inputs from limbic areas coding for stimulus salience [77].
For example, many birders have expertise for both visual appearance and birdsong, experts in other domains
have both visual and haptic experience objects, and most of us readily identify people using their face and
their voice. For example, faces may become “special” in infants through the temporal co-occurrence of
the parent’s face and voice [78]. In the following projects, we will explore experimentally the temporal
dynamics of such multimodal interactions in object expertise. We will develop computational models where
different modalities mutually train one another to learn better classifications.

**Specific Projects** 4. The Sound an Object Makes and the Way an Object Sounds. Our first studies
will contrast audio-visual integration where auditory information is either temporally correlated or uncor-
related with object shape. For example, sonification [79] creates soundscapes that are systematically related
to object shape, with amplitude of a sinusoidal oscillator proportional to pixel gray level, frequency propor-
tional to the vertical elevation of the pixel, with time moving horizontally across the image. With practice,
sonification has been shown to improve identification in both blind and sighted observers [80]. Temporal
synchrony of shape and sound is created by visually presenting the object through a narrow vertical window
time-locked to the left-to-right sonification of the image. As a contrast to sonification, unique uncorrelated
auditory information can be associated with individual shapes using synthesized voices speaking a nonsense
language. Unlike sonification, synthesized voices have no natural relationship to object shape, though it is
possible to parametrically manipulate voices so that objects in the same category have more similar voices.
These two approaches to audio-visual integration are complementary. Using sonification, we associate shape
and sound to reproduce the sorts of non-arbitrary correlations observed naturally in other situations, such as
vision and haptics. Using synthesized voices, we reproduce more arbitrary pairings observed between
faces and voices [81] or between artifacts and their sounds. We will train experts in audiovisual conditions
using artificial stimuli (such as Greebles) and an expertise training protocol that we understand well under
unimodal conditions [82, 83, 59]. A number of tests will be conducted pre- and post-training. We will
assess whether acquisition of expertise under these different training conditions influences typical markers
of unimodal expertise such as holistic and configural processing, magnitude of the FFA response, and prop-
erties of the N170 and N250 ERP components. In addition, we propose to employ transcranial magnetic
stimulation (TMS) to regions of the superior temporal sulcus (STS) that may be involved in our audiovisual
integration (identified via fMRI) to create reversible lesions. By briefly disabling select neural tissue, we
can assess for behavioral deficits in integration, and more clearly specify the information-processing role of regions accessible to TMS. This will allow us to link the STS activity to bimodal behavioral effects.

Our current models of expert perception are unimodal; however, multimodal learning has been put forward as an alternative to supervised learning models [78]. The idea of the minimizing-disagreement algorithm (M-D) is to have networks operating in different modalities learn to minimize their disagreement concerning the category of a stimulus. In the audiovisual domain, this method has been shown to rival standard supervised training algorithms [78]. The empirical work has shown that the approach works best when the patterns for different categories are highly separable but also when the two modalities are conditionally uncorrelated. Not surprisingly, for easiest learning, the classes of both auditory and visual patterns should be highly discriminable; that is the auditory patterns for one visual category, should be very different than those for another visual category. But within this constraint, the auditory sounds created for a particular visual patterns should be generated randomly from the set of auditory patterns for that class. This predicts that the sonification training should not be as effective at the synthesized voices method at improved learning over the unimodal method. In fact if multimodal input is a full replacement for the label signal (if no other feedback is given to the subject), the M-D algorithm predicts that the sonification method will fail [84]. It will be interesting to compare this prediction with the training results.

5. The Role of Affective Modulation on Expertise Acquisition. There is emerging interest in how emotional centers of the brain may influence perception by altering the prioritization of attentional resources[85, 86, 87, 88]. Stimuli that are more emotionally arousing (e.g., fear related) show increased activation of both medial temporal limbic areas and perceptual areas of cortex [77, 89]. For example, viewing a fearful face compared to a neutral face produces more activation in face responsive IT areas [89, 90]. Similar findings have been reported with single cell recordings in monkey visual cortex [91]. A prevailing view is that perceptual processes are enhanced by re-entrant inputs to visual areas from limbic regions over time, especially from the amygdala. Recent fMRI data reveal a task-dependent correlation between the amygdala and FFA, with the correlation stronger during face perception than during object perception [92]. We aim to use a combination of behavioral manipulations, fMRI, and ERP to unravel how emotion might actively modulate activity in the ventral temporal visual pathway over time. We will examine how interactions between amygdala and FFA might impact the acquisition of perceptual expertise with novel stimuli over time. Moreover, in disorders where face expertise fails to fully develop, such as autism, there is reduced modulation [92]. This paradigm will provide a basis for a testable model of the role of affective inputs to enhanced perceptual skill.

6. Cross-Modal Transfer of Improved Temporal Processing. The nature of temporal processing within and between different modalities may have important implications for understanding dyslexia and other language impairments. Individuals with dyslexia have impaired temporal processing in both audition [93] and vision [94]. Paradigms where the stimulus is slowed down for recognition and then slowly sped up through training with constant performance monitoring and feedback (shaping) have been effective for improving the auditory temporal processing of children with language deficits and improves their reading level [95]. But does improving auditory temporal processing transfer to help visual temporal processing? Can training both simultaneously lead to faster learning? Does improving auditory temporal processing by shaping lead to cross-modal transfer? More specifically, if we train subjects to have a faster auditory system, does their visual processing similarly speed up? Can we improve learning by training both visual and auditory temporal processing? We will test these questions behaviorally using auditory and visual masking paradigms as well as visual motion discrimination tasks for different motion speeds. In addition we will use EEG recordings to observe brain responses to two visual flashes or clicks presented at varying ISIs. Responses to visual and auditory stimuli before and after temporal training will be compared. Cortical surface-based fMRI will be used to investigate whether, after temporal training, how auditory and visual areas are differently activated by the fast temporal auditory and visual stimuli. To detect training effects, between-session variance must be minimized. Marty Sereno has extensive experience with this and has routinely obtained reliable retinotopic maps of both intermediate (e.g., V3A) and higher level (e.g., LIP) visual areas[96] in single subjects over time periods of several years.

From a computational modeling perspective, can we train a neural network that demonstrates shaping-improved temporal processing? We will first train a network to cluster temporally low passed inputs of spo-
ken consonants. Then we will remove the input distortion and let the clusters adjust. This would represent the ability of the network to adjust without behavioral shaping. To contrast, we will apply a reinforcement-learning signal and slowed down versions of the inputs that will adapt as the network improves (using the behavioral shaping paradigm from above). This work will build on recent work by Triesch [97] as well as Sullivan and de Sa [98] to investigate homeostatic mechanisms for regulating plasticity. But can we train a self-teaching neural network using temporally appropriate signals? Our Minimizing-Disagreement (M-D) algorithm, like most pattern recognition algorithms, treats time as another spatial dimension. In order to fully model the shaping training, we will make a more realistic distributed and dynamic version of the M-D algorithm by building on the temporal aspects of our more recent algorithms [99]. The results of our studies may be used to improve learning in systems such as SLC’s Fast ForWord intervention program.

3.4.3 Tracing the Acquisition of Perceptual Expertise

Overview Numerous perceptual expertise studies have examined differences between real-world experts (e.g., dog experts and bird watchers) and novices [64, 66, 100, 101, 56, 102], but less attention has been paid to the details of the learning processes underlying expertise acquisition. Understanding these learning processes has both practical and theoretical implications outside of the laboratory, including clinical domains and classroom learning. Collaborative efforts will focus on exploring the impact of exposure and feedback learning on long-term neural and behavioral changes related to expertise and how this new learning interacts with preexisting capacities. These efforts will intersect with the Human Brain Dynamics group who is investigating how reward and reward timing influence learning. Of great interest is how temporal dynamics of individual learning episodes interact with the far longer temporal dynamics of learning over weeks or months.

One resource we will make use of is the database of learning trajectories followed by children learning with the Fast ForWord program. These children’s progressions, mouse click by mouse click are recorded into the database as they work on several different training tasks ranging from speed of processing tone sequences, to making fine grain acoustic distinctions within confusable phonemes, to phoneme categorization, to recognizing confusable pairs of phonemes in word context, to learning all of the explicit rules of English grammar, to learning letter sound correspondence rules for reading. The children begin as non experts and many of them end up as well within normal limits after intensive daily practice on exercises organized to move them from easy to harder items, based on their own individual trajectory of responses. The database has all of these data organized, graphed and trajectories on each task over days is recorded. We will use the database to examine whether the learning trajectories of the improvement in auditory processing speed predict the development of perceptual expertise in phoneme categorization or the learning of grammatical rules. We will also examine whether the shapes of the learning trajectories predict specific outcomes. The outcome of this work will be directly useful for improving intervention programs such as Fast ForWord.

7. Perceptual Experience versus Perceptual Expertise The importance of normal sensory experience in the organization of developing brains is well established [103, 104], but the role that raw experience plays in the reshaping of mature cortex is less clear. Behavioral evidence suggests that feedback-driven subordinate-level training rather than incidental perceptual exposure alone is important for the acquisition of expertise. Training studies also show that learning subordinate categorizations with feedback not only promotes the rapid and specific identification of expert objects, it also facilitates the transfer of subordinate recognition to novel stimuli within the expert domain [59]. On the other hand, repeated exposure to specific objects can lead to clear changes in neuronal responses to familiar items compared to similar, but unfamiliar, exemplars. We have observed such effects in monkeys [105], humans [67], and in predictions of some computational models [106, 107].

A differential influence of raw experience versus learning with feedback appears at temporal markers of recognition, the N170 versus N250 ERP components, respectively [67]. These ERP components have been used as important neural signatures underlying expertise. Differential impact of brain damage on these temporal markers can be important for understanding disorders like autism and congenital prosopagnosia. And relating ERP components across humans and monkeys may prove a useful tool for bridging between human studies of brain activity and monkey studies of neurophysiology. There is a clear need to tease apart effects
of exposure from those of supervised learning in a coordinated effort combining neurophysiology, ERPs, fMRI, and patient studies. We will study whether mere exposure may serve as a springboard for expertise, and whether temporal ERP markers such as the N170 and the N250 may distinguish between exposure and feedback learning. In addition to comparing exposure and feedback on learning and the temporal markers of expertise, it is also important to understand how the temporal dynamics of exposure trials and feedback trials influence their impact on expertise. The timing of exposure trials can have an impact on the efficacy of exposure to perceptual learning. The timing of corrective feedback can have an impact on the efficacy of feedback learning. To better understand the complex interactions between exposure and feedback on learning and the temporal dynamics of expert decisions, we will turn to computational models. The models will contain computational equivalents to electrical potentials, and we will assess the differential role of exposure and feedback learning in the model and its electrophysiological predictions [108].

8. Let’s Face It!: A Face Training Program in Autism Individuals diagnosed with autism spectrum disorder are characterized by delayed language abilities, repetitive and restricted behaviors and impaired social emotional function. An emerging body of research indicates that children with autism also show selective deficits in face recognition. Therefore, it should not be surprising that children with autism experience difficulties in social situations that require fast and accurate interpretation of dynamic facial cues. Can face recognition impairments in autism be improved through direct intervention? If face processes are analogous to other types of perceptual expertise, they should be amenable to similar types of training effects [83, 109] eliciting similar changes in neural plasticity [110]. Toward that objective, we will continue development and evaluation of the Let’s Face It! (LFI!) program as a computer-based intervention to teach face processing skills to children with autism. Based on the principles of expertise training, the child progresses through a hierarchy of interactive games in LFI! targeting the fast and accurate recognition of facial identity and expression. Similar to SLC’s Fast ForWord intervention program, the LFI! platform employs an intelligent tutoring method that dynamically adapts to child’s current skill and ability level. In addition to cognitive and social-emotional measures, brain scans of the children will be taken prior to and after their participation in the two-month treatment program to measure potential changes in neural activity. The goals of the face-training project are to enhance the face processing skills of children with autism and assess learning-related changes in social adaptation and neurofunctional function.

9. Is a Little Knowledge a Bad Thing? Can expert processing emerge for any sufficiently complex object class given adequate training? Some studies support this general idea [64, 109, 59, 100, 102]. However, some attempts to show that expertise will emerge following significant training protocols have not been successful with normal adults. For example, extensive training with inverted faces led to improved recognition but did not reveal holistic composite effects found for upright faces [111]. Instead, subjects relied on part-based analyses that are generally observed when holistic processing breaks down, as in the case of prosopagnosia [112]. It is possible that processes responsible for developing new domains of expertise may be short circuited by existing specialization for related stimuli. A variety of processing architectures could explain such a short circuit. One simple model of temporal dynamics is the horse race, where strong preexisting representational schemes win out over any new representational schemes that might attempt to be created. We will explore the proposition that highly developed expertise in one subdomain may in fact interfere with the acquisition of expertise to other stimuli. For example, training a neural network to expertise with one object category facilitates acquisition of expertise with another category [106], but it is possible that interference would occur in special cases, such as for different orientations of the same objects or categories that are very similar in one way and not another. Will there be negative transfer in learning a new domain because of expertise in another domain? And will such negative transfer be observed in the usual neural markers of expertise?

3.5 The Social Interaction Network

Social interaction plays a vital role in the learning process, from learning about objects in the environment through shared attention to classroom learning. Behavioral responses at time scales of milliseconds to seconds can profoundly influence the success of these social interactions. The research in this section explores the dynamics of behaviors such as gaze following, pointing, and reciprocity of expression and gesture, how
they develop, and how they impact learning at higher levels. Social robots are a medium for studying the integration of perception and action in real time, and for understanding how the dynamics of social cues and responses can influence student engagement, and ultimately their ability to learn. The second project explores the timing of nonverbal as well as verbal interactions of students and teachers. It describes the dynamics of facial expression, gesture, and reciprocity in teaching, and provides a model for social dynamics in teaching robots. The third project explores the development of shared attention in infants, and how sensitivity to temporal contingencies influences gaze following. The fourth project explores human brain dynamics of learning by simultaneously measuring EEG in pairs of subjects during continuous interaction tasks.

Affective state alters neuromodulatory levels, which in turn may alter the dynamics of time-dependent synaptic plasticity, as discussed in the Sensorimotor Learning section, and appears to also alter the activity levels in perceptual pathways, as described in the Perceptual Expertise section. Automated facial expression measurement developed by the research team in the Social Dynamics network, provide an assay of emotional state that will enable further investigation of these questions through collaboration among the members of these networks.

3.5.1 Interactive Robots for Learning and Education

**Research team:** Javier Movellan, Director of the Mahine Perception Lab at UCSD, Robert Mainieri, director of the Robotics Team at the Preuss School, and Kathryn Owen, Director of the Early Childhood Education Center.

For the first time in history the development of social robots that interact with humans and assist them in their daily activities has become a technological possibility [113, 114]. Social robots have to operate in a world in which timing and uncertainty are of the essence. This is forcing researchers to focus on the problem of how to integrate perception and action in real time, rather than the scholastic study of the faculties of the mind (attention, memory, concept formation). One key target of the social robotics movement is educational and learning environments. Indeed robots have great potential as an educational medium: They are engaging, personable, and interactive. Social robotics is teaching us that genuine interaction will have to go far beyond computing capacity or sterile cognition. It will have to be about forming relationships.

Last year, as part of a collaboration between Sony and the University of California, we developed a robot, named RUBI and immersed her for a period of 3 months in the daily activities of the Early Childhood Education Center at the University of California San Diego (see Figure ??). In this section we propose to extend the ideas of the RUBI project and integrate them with the rest of the activities in the proposed SLC.

The robots we propose to construct will be a shared resource for the SLC to be used not only as teaching tools but also for many of the projects in the proposed SLC. For example, the robots will be used by Scott Makeig’s group to understand the brain dynamics of real time social interaction during learning. Robots allow control of a wide range of interaction parameters, thus helping elucidate which parameters the brain is particularly sensitive to. The robots will also be used for testing theories about how children learn to share attention as part of the MESA project [115].

**Robot Construction.** We propose to construct 2 robot prototypes, one targeting pre-school and elementary school age education, and one targeting middle-school education. The construction of the robots will be led by Javier R. Movellan, director of the Machine Perception Laboratory at UCSD, and Robert Mainieri, director of the Robotics Team at the Preuss School. The Preuss School, is a charter school at UCSD for low-income student in grades 6-12. Preuss 2004/05 demographics are: 59.5% Hispanic, 12.9% African American, 21.7% Asian, 6% White. The Preuss School Robotics Team is modifying the way youngsters view careers in engineering and manufacturing as well as the methods by which math, science, and technology are taught. The robot construction proposed here will be done at the Preuss facilities and will be part of a new experimental curriculum in robotics at Preuss.

The two robots will be based on the original RUBI design [116]. They will have a head with three degrees of freedom, two arms, and a touchscreen. The actuators will consists of a 12 inch touch video screen, 3 speakers, and 13 servo motors to control the neck, cameras, and facial expressions. The robots will be powered by a cluster of 4 computers connected via high-speed Ethernet. The robots will be endowed
Figure 4: LEFT: RUBI is a social robot designed at UCSD’s Machine Perception Laboratory to interact with children. It can find faces, read facial expressions and understand a few English words. It can communicate via head movements, hand movements, and sounds. RIGHT: A collage of faces automatically detected by RUBI in a session at ECEC.

with the latest perceptual primitives developed at the Machine Perception Laboratory at UCSD, including face detection, pose estimation, expression recognition, and infomax control.

The “B” in RUBI stands for “Bayesian”, to remind us of an ultimate goal of developing an architecture that combines perception and action in a principled manner using probability theory and the theory of stochastic optimal control. Last year we developed an early example of the approach and named it Bayesian Infomax Control [117]. This approach uses the theory of stochastic optimal control to frame the problem of timing behaviors in an uncertain and continuously evolving world. We propose to continue development of the Infomax Control framework and adapt it to the problem of real time learning and tutoring. The goal is for the robots to choose the educational material most likely to provide information and improve the knowledge state of the students.

**Immersion, Continuous Exploration, and Evaluation.** Following the philosophy of the RUBI project, we propose to immerse the robots and researchers 1 hour a day, at ECEC and the Preuss School. The performance of the robots will focus on two basic metrics: (1) goodness of the interaction; (2) Learning Effectiveness. We found continuous audience response methods borrowed from marketing research [118, 119] to be particularly effective for evaluation of goodness of interaction. Every day 3 coders will view the tapes of the interaction between students and robots and evaluate goodness of the interaction using a rotating knob in real time. We found this method provided good inter-observer reliability, in the range of 0.8 - 0.9 Spearman correlation coefficient.

In addition at each experimental session the robots’ perceptual systems will record the images of the people they detect, the number of smiles she detects, the frequency and timing of contacts in their touchscreen, and whether such contact represented correct or incorrect responses to her questions.

By the end of the second year into the project we will start to rigorously evaluate the effectiveness of the robots as a tutoring systems. One of the issues at hand is whether the one-on-one personal tutoring provided by the robot platforms compares with traditional computer tutoring system, and with human tutoring.

### 3.5.2 Modeling real time social interaction during learning

**Research team:** Marian Bartlett, Javier Movellan, and Gwen Littlewort are expert in automatic measurement of facial expression and automatic coding of the Facial Action Coding System. Judy Reilly is expert in language and facial dynamics in learning.

**Social rapport and information transfer** When people reach a state of rapport, they tend to exhibit behaviors such as mirroring expressions, head movements, and gestures, as well as matching voice tones
and increase in touching [120, 121, 122]. Research shows that this matching of behavior has a subconscious affect on individuals, making them feel more relaxed, more open, and to like the interaction considerably more [123]. There is some suggestion that such behaviors also increase information transfer between individuals [124]. The proposed center includes careful study of social rapport during teaching – how it is characterized, whether deliberate attempts to mirror facial expressions and posture help build rapport, and whether such behaviors lead to increased learning and information transfer. We will also explore how reciprocity and mirroring behaviors are altered when the teacher and student are a different gender, a different race, or come from different cultures. The concept is that nonverbal dynamics on time scales of seconds and milliseconds can influence learning on the time scales of a tutoring session, a semester, or a year.

A major focus of the Social Interaction group is automated recognition of nonverbal behavior such as expression, head movement, and eye gaze. For the last three years, the Machine Perception Lab at UCSD has been engaged in an NSF project for automatic analysis of spontaneous facial expressions (NSF IIS-0220141), as well as another NSF funded project to create a new generation of teaching software that understands the facial expressions of students and that interacts with them via computer animated characters (NSF IIS-0086107). Expression measurement tools enable automated tutoring systems that recognize the emotional and cognitive state of the pupil and respond accordingly. Such systems would also assist robots and animated agents to establish social resonance.

**Analysis of Teacher - Student Interaction** We propose to collect a dataset specifically designed to investigate the statistical structure of social interaction during teaching engagements. This dataset will enable quantitative characterization of verbal and nonverbal behavior in human social resonance and student-teacher interaction, and comparison of the dynamics during effective versus ineffective teaching interactions. This will provide critical information on the role of nonverbal behavior in teaching, as well as for efforts to make computers and robots that interact effectively with humans. For example, when a teacher sees that a child is frustrated, does he/she mirror the child’s expression and if so for how long? How does that correlate with eye contact? What are the nonverbal characteristics associated with good teachers, successful outcomes, and greater learning?

We propose collecting 200 minutes of Teacher-Student interaction using the facilities of the proposed Motion Capture Laboratory. The dataset will include children from preschool, elementary school, and middle-school age groups, in order to inform the student-robot interaction work which focuses on those age groups. Each child will individually interact with a teacher in the motion capture facility while the teacher introduces them to a challenging but age appropriate mathematical concept. In addition to the motion capture of gesture dynamics, we will employ automated facial expression measurement tools already developed in the Machine Perception Laboratory (e.g. [125]) to study facial expression dynamics of teachers and students. Automated facial measurement has already been shown effective for the study of mother-infant reciprocity and synchrony of smiling [126]. Moreover, in collaboration with Judy Reilly, we will undertake analysis of verbal as well as nonverbal behavior including language content, facial expression, gesture (if that is still the case) and their temporal relations.

The data will be used to develop statistical dynamical models [127] that capture the timing of the head movements, eye movements, and hand/arm movements and facial expressions of students and teachers. These models will be used to increase the effectiveness of the social robot, RUBI, which is designed for education environments.

In collaboration with the teachers and students at Preuss, tutoring sessions will be systematically varied by gender, race, and cultural background of the participants in order to investigate differences in nonverbal interaction dynamics when teacher and student differ along these dimensions. These tutoring sessions will be recorded in the Motion Capture Facility in order to allow us to quantify the temporal cadences associated with differing communication styles. This investigation will allow us to answer questions concerning the effect upon tutoring outcomes of matches and mismatches in communication styles between teachers and students. In addition, we will explore cross-cultural issues with respect to the use of eye gaze as well as facial expression, both affective and communicative. The Reilly lab recently showed that American children categorize neutral faces as generally negative, whereas the French children categorize them as generally positive. This gives support to the hypotheses that culture and (probably) gender differences are going to play a role in how teachers use facial expression, and also how the children interpret them, and ultimately
the success of the interactions.

3.5.3 Modeling the Emergence of Social Attention in Human Infants (MESA)

Research team: Gedeon Deák (Cognitive Development Lab) and Jochen Triesch (Complex Systems and Cognition Lab), in collaboration with Leslie Carve and Javier Movellan.

How do human infants learn to adapt their behaviors to other people, and predict other people’s actions? These are hard problems because everyday social interactions are fast, information-packed, and variable. In typical infants, social skills and sensitivity change radically from birth to 12 months. Neonates cannot recognize specific faces or shift their attention quickly; by 12 months they have quite sophisticated attention-sharing skills, including gaze-following and point-following, critical social skills for teaching and learning. How do these skills emerge? Certain fast neural learning processes are operating in very young infants. How do these processes explain the development of new skills over weeks and months?

Our theory [128] focuses on a reinforcement learning model (TD-learning) [38], wherein infants register short- and longer-term consequences of various actions, and gradually develop action “policies” to maximize positive outcomes, in the long run. Our model adds to this a habituation process, by which infants lose interest in experiences over time, and seek out new and more rewarding stimulation. To refine a theory of social learning, we use data on real infants’ social responses to caregivers’ behaviors. We model these data in real-time embodied computer simulations, featuring virtual infants and caregivers.

Initial work was funded by seed grants from the M.I.N.D. Institute (UC-Davis) and National Alliance for Autism Research; the main study has been recommended for a 3-year award from NSF (Human Social Dynamics).

The MESA project (Modeling the Emergence of Shared Attention) has a growing database of video-recorded naturalistic observation of caregivers and infants at play. So far we have well-controlled video of over 30 infant-parent dyads recorded in their homes. Caregivers’ actions are coded in high detail from digital video files [129] using a specialized computer coding interface. We look for predictable caregiver action sequences that infants might learn from, and learn to predict. Here “predictable” refers both to orders and timing of various possible caregiver actions. A guiding research question has been how infants learn that a caregiver’s shift of gaze, or pointing toward something, predicts the presence of some interesting object or event. Future work (with Leslie Carver) will also focus on how infants also learn to use caregivers’ emotional expressions to predict future events. This ability, called social referencing, is a critical means for using social information to interpret ambiguous situations [130].

Our planned study is a longitudinal study of infants’ attention-sharing skills as they develop from 3 to 12 months of age, as a response to their caregivers’ predictable behaviors. In planned observational studies we will use a specialized, non-obtrusive multiple camera system to record video each month in infants’ homes. With the SLC motion capture facility, we will also record two play interactions. The precise location data captured in this facility will provide unprecedented accuracy in describing the temporal synchrony of each infant-parent pair. We will also test infants’ gaze- and point-following abilities, month-by-month, in controlled laboratory procedures. In addition, we will assess individual infants’ perceptual and learning capacities, including habituation, visual event prediction, and face discrimination. Our goal is to relate changes in these capacities, month by month, to individual infants’ changing social attention skills. This effort is supported by computer simulations that point to these perceptual and learning processes as critical factors in learning gaze-following [131].

The robotic platform, RUBI, we will be able to control the timing parameters of social cues (e.g., gaze shifts; pointing), and study children’s response to these cues. With the robot we can manipulate the delay and variance of the timing of contingent behaviors to see how that affects the emergence of shared attention with the robotic agent.

With support from the Center we will directly test new predictions of the theory by extending our simulations of infant-caregiver interactions. In particular, we will build more realistic spatial representations in the model, and make better simulations of caregivers and infants hands and arms (in collaboration with Emo Todorov), to extend the theory to the development of pointing, point following, and manual imitation.

Support from the Center will also allow us to extend the longitudinal behavioral study to new groups
of infants with specific developmental disabilities: Williams syndrome (studied by Kang Lee) and infant siblings of children with autism-spectrum disorders (Leslie Carver will collaborate to study this population). We have promising simulation results that seem to capture behavioral differences in children with Williams syndrome and autism, in their gaze-following skills [131]. All video and coded behavioral data from the MESA project will be contributed to the Learning Dynamics Grid, for confidential availability to other researchers in the SLC program.

This project will also enable studies of multimodal perception and learning. Caregivers provide visual, auditory, and tactile cues during social interaction with infants. We know very little about how temporally coordinated multimodal cues provide useful input to infants. (Perhaps, for example, predictable multimodal cues will be critical for teaching new social strategies to children with autism.) The MESA project’s extensive video database of infant-caregiver interactions, with precise timing information, will be used by Virginia de Sa, Gedeon Dek and Jochen Triesch to extend theories of how infants learn from multimodal caregiver cues.

3.5.4 Human Brain Dynamics of Learning

Research team: This work will be directed by Scott Makeig at the Swartz Center for Computational Neuroscience, in collaboration with Paula Tallal, Virginia de Sa, Gedeon Deák, Jochen Triesch, Gwen Littlwort, Marian Bartlett, Javier Movellan, and Terrence Sejnowski.

This project will combine new recording and analysis methods for imaging human brain dynamics. We will record, measure and model human brain dynamics during solo learning/practice, human-computer and human-robot learning, formal teacher-student learning and peer-peer social learning. The primary laboratory tools will be high-dimensional EEG (256 channels from one subject or 138 channels on each of two subjects) synchronized to 1-4 channel digital color video. In other experiments, high-density EEG will be combined with concurrent very high dimensional MEG (UCSD Neuromag MEG system) or with concurrent fMRI BOLD (UCSD Functional MR Imaging Center) recording.

A major problem for most human brain imaging using EEG/MEG and/or BOLD is that the dimensionality of the recorded brain dynamics is much higher than the dimensionality of the recorded behavior (e.g., typical button-press choices and reaction times). Furthermore, the typical approach of averaging evoked responses can miss a great deal of the important dynamics in the data. We will therefore attempt to increase the dimensionality of the dynamic behavioral data recorded, using both extrinsic and intrinsic measures: eye tracking and psychophysiological measures (respiration, galvanic skin response, electrocardiogram, electromyogram), collaborative analysis of multi-channel face video, 3-D joint position and movement imaging (using the proposed Motion Capture facility). In some experiments, high-density EEG will be combined with simultaneous very-high density MEG, using the new UCSD MEG/EEG facility, and/or with 3-Tesla fMRI imaging (Serenus), using the proposed Spatiotemporal Imaging facility.

Rather than focusing only on results of event-related response averaging, we will attempt to identify relationships between the event-related variability of the observed brain dynamics, in single trials and during continuous task performance, to the ever-changing brain and behavioral event context (including the brain and behavioral history and resulting expectations). Projects will include:

1. A study of the relationship of reward and reward timing to behavioral and brain dynamics of learning (Makeig, Sejnowski). Recent EEG results by Makeig and others have demonstrated a correlation between the dynamics of perceived reward or punishment on the part of the subject and a greater power in theta rhythmicity over frontal sites [132, 133, 134]. These results have recently been confirmed by direct intracranial recordings in humans undergoing clinical monitoring [135]. The ultimate goal of this research will be to discover the relationship among top-down reward monitoring, attention shifting and motor planning systems.

2. We will study the relation of high-dimensional EEG brain dynamics to the timing and directions of active eye movements and facial expressions during exploration, search and associative learning tasks in human-computer interaction (Makeig, Deak, Triesch), and the generalization of fast temporal learning between modalities (audition and vision) (Tallal, de Sa).

3. We will apply the results of brain dynamics studies (above) to the design and testing of more efficient
training methods. Despite the finding that performance-based feedback facilitates cortical plasticity[136], the effects of reward timing relative to response output have been little explored in humans since the era of behavioral learning theory. Performance-based rewards may be implicit (self-satisfaction from attaining goals or sub-goals) or explicit (objective rewards and praise). We propose to explore whether the course of training can be enhanced by adding real-time brain dynamics-based rewards [137] selected and timed to encourage the learner to produce brain dynamics associated with their successful performance in their other training sessions. Key questions here will be the nature of the brain patterns to be rewarded, and the nature and timing of the reward feedback.

3.6 Cross-cutting Facilities

3.6.1 The Spatio-Temporal Brain Dynamics Facility

The proposed Spatio-Temporal Brain Dynamics Facility will allow center investigators to study the brain dynamics of learning by exploiting simultaneously the excellent temporal resolution of EEG (high-density Electroencephalograms) and the good spatial resolution of fMRI (functional magnetic resonance imaging). This emerging technology allows researchers the see how brain areas modulate with learning and measure the precise changes in the time course of that modulation during perception, action, or thought. Serious obstacles to simultaneous EEG and fMRI as a true functional brain imaging modality are the acute EEG contamination produced by the MR and fMR environment, and the rudimentary dynamic data modeling (evoked response EEG averaging, regression- based fMR modeling) normally applied to the data. The major challenges for developing true joint EEG/fMR imaging of brain dynamic brain processes linked to learning and behavior, therefore, are how to minimize EEG artifacts during recording and/or how to eliminate recorded artifacts in post-processing, and how to more adequately model the rich brain dynamics contained in the jointly recorded signals.

The proposed facility will utilize the custom EEG-in-MR system developed by Makeig, Sejnowski and collaborators over the past seven years (Jung et al., 1999, 2004; Makeig et al., 2002a; Finelli et al., 2002, 2003). This 64-channel system combines a custom-designed non-magnetic electrode cap with redundant twisted pair carbon leads, a custom-built lead support gantry, battery-powered amplifiers housed in a custom titanium shielding box, and battery-powered, fMR- synchronized A/D converters. This system will be installed in one UCSD Functional Imaging Center 3-T GE scanner. Subject behavior will be tracked with various finger button sensors available at the fMR Center and by in-scanner eye tracking. Data analysis will combine independent component analysis with regression-based pulse and ballistocardiogram artifact removal methods (Jung et al., 1999, 2004; Finelli et al., 2002, 2003; Makeig et al., 2002), performed by a validated plug-in facility (Niazi,) in the Matlab-based open source EEGLAB (Delorme & Makeig, 2004) and FMRLAB (Duann et al., 2002) environments. Data analysis methods available in those environments include available methods for independent component analysis of both the IMRI (Duann et al., 2002) and EEG data (Makeig et al., 2002b, 2004), time/frequency analysis, and other approaches including ready conversion to other standard analysis packages (SPM, AFNI, Freesurfer, Brainstorm, FieldTrip).

3.6.2 The Data Sharing Facility

A large scale data-sharing facility will be established as a cross-cutting resource. We will develop a Data Sharing Database for the dissemination and manipulation of processed data and a Data Sharing Grid for the storage, fluid retrieval, dissemination, and large-scale analyses of raw data.

**Data Sharing Database:** The goal of this component is to accelerate the ethical and efficient sharing of data between researchers. Dr. Mark Appelbaum of UCSD is a nationally known expert in developing tools for interdisciplinary data sharing and validation. He has practical experience with problems of data structure and data analysis in large, multi-site studies such as this one. He has agreed to provide the infrastructure and intellectual leadership for sharing data between the many researchers in the center in ways that allow for confidentiality, provide procedures for updating data when mistakes must be corrected, and incorporate data annotation tools so that other researchers may reliably use the data and replicate experimental methods.
Data Sharing Grid: In addition to sharing highly processed data, we intend to extend the concept of data sharing to relatively “raw” experimental data. This will be accomplished in conjunction with the San Diego Supercomputer Center, in collaboration with Arcot Rajasecar [138, 139, 140, 141], Director of the Storage Resource Broker (SRB) group. The San Diego Super Computer Center has developed the Storage Resource Broker (SRB), a software platform of choice for the development of datagrids [142, 143]. A data grid is a software infrastructure that supports access to data and information distributed across repositories. A data grid provides a data virtualization service, making it possible to organize distributed files into a logical collection that appears to be locally accessible. In scientific communities, data grids are becoming increasingly important for sharing large data collections in collaborative environments. In addition to utilizing this environment for the sharing of raw data (such as EEG, fMRI, single and multiunit neural recordings, video, and motion capture data), we intend to use the Storage Resource Broker (SRB), a data grid infrastructure, for fluid access to experimental stimuli and novel computational architectures.

Consider the following scenario that illustrates the possibilities of Data Grids:

Scott Makeig’s group at UCSD has a local copy of the EEG recordings made by David Sheinberg’s lab at Brown while monkeys were learning to become experts at classifying certain visual objects. His group applies their Independent Components Analysis tools to Sheinberg’s data in order to remove artifacts and find the independent sources of the signals. Immediately, this new analysis becomes available to all the laboratories authorized to use the Data Grid. The Data Grid now contains not only the “raw” EEG, but the processed EEG, along with the JPEG images that evoked these responses from the monkeys in the experiments. Makeig has not yet analyzed the components, so they are labeled “development version 1.0”. The next day, Makeig decides that some of the components are noise and relabels the components “stable version 1.0”. Tim Curran, whose laboratory in Boulder is authorized to connect to the Data Grid, queries the relational database server at UCSD. He had previously submitted his EEG data from humans trained on the same stimuli as Sheinberg’s monkeys, and had them analyzed by Makeig. Now he is able to compare directly the processed EEG components from the monkeys to the EEG components evoked in humans learning to categorize the same stimuli. The system is able to line up the data according to the images used as stimuli. Local copies of the images do not exist on Tim’s server, so they are automatically retrieved from the closest server with copies of the images.

Additionally, we will work with the experts at the supercomputer center to align multiple sets of raw data along meaningful dimensions. One such dimension will be timescale. The examination of how stimuli, brain responses, and behavioral responses correlate with one another will be accomplished by using unsupervised machine learning techniques to find meaningful clusters across multiple time scales. This technique can only be applied in an environment where distributed, remote, files can be made fluidly accessible.

We envision our “Data Sharing Grid” as model of data sharing and large scale analysis technology, and expect it to be the prototype of an essential tool for researchers in other NSF Science of Learning Centers. Examples of Data Grids can be found in the physics community [144, 145], climatology [146], and ecological sciences [147]. Data Grids are also being developed for research communities such as astronomy [148], geography, plate tectonics [149, 150], NASA’s Information Power Grid [151], and the DOE’s Advanced Simulation and Computing grid [152]. Eventually, our Data Sharing Grid will allow transparent and authenticated access to datasets for which there may be multiple copies distributed at different laboratories across the world.

3.6.3 The Motion Capture Facility

The University of California San Diego has committed to provide 800 sq-ft for a portable Motion Capture Facility that will be shared by all the researchers involved in the proposed SLC, as well as with other researchers throughout the nation. The facility will include a portable Vicon motion capture system, 4 data gloves, an eye tracking system, and 4 synchronized professional digital video cameras. The Motion capture system, will consists of 16 specialized infrared cameras which can be spaced around a room, allowing to
triangulate the exact position in 3D space of each of a large number of small reflective markers every 1/120th of a second (8.33 ms). The position of these markers is then fit to an articulated model of the human body thus providing very detailed information about critical aspects of the of the dynamics of social interaction. For example, the system can provide information about the relative orientation of the head of tutors and students as learning progresses. This could be used to understand which sources of information are used by tutors to assess the emotional and knowledge state of the students and to adapt their tutoring strategies accordingly.

One of the goals of the Motion Capture Facility will be to enable collection of a variety of datasets focused on the problem of real time learning dynamics. These will include a dataset of one-on-one tutoring interactions, a dataset focused on the problem of how infants learn to share attention with adults, and a dataset that combines simultaneous motion capture and EEG during learning. The Center’s activities in the motion capture center will be headed by Javier R. Movellan, one of the project’s Co-PI’s. Javier has experience working with a similar facility at the Advanced Telecommunication Research Laboratories in Kyoto, Japan for the past 3 years.

4 Integration of Research and Education

4.1 The Education and Outreach Center

The Education and Outreach Center, led by Terry Sejnowski and Paula Tallal, will oversee all of our Education and Outreach activities, and be a conduit for all of the networks to get their message out. Our education program has several components designed for different populations, as outlined below:

Mechanisms for Training High School Students and Teachers  First, in partnership with Reach for Tomorrow (RFT) (http://www.reachfortomorrow.org/), we will provide summer workshops for inner city high school students, as well as Native American, Inuit, and other underrepresented minorities. These workshops will expose students to cutting edge research in the science of learning. RFT has been associated with UCSD for ten years, with a proven track record of moving students into science. In 2004, 90 predominantly African-American and Hispanic students spent two weeks at UCSD, where, among other things, they learned neural network and cognitive modeling. This summer, 35 Alaskan Native students will visit UCSD for two weeks and be exposed to, among other topics, our work in Vision and Learning in Humans and Machines, using interactive demonstrations led by Marni Bartlett and fellows in our training program.

Second, we will work with students and teachers from the Preuss School, a UCSD-sponsored charter school that has an excellent record of sending its predominantly minority students to four year colleges. Students will conduct research rotations in our laboratories as a way to prepare them for research careers before they go to college.

Third, we also hold Summer Science of Learning Workshops for high school teachers. We have found this to be an excellent vehicle for exporting state-of-the-science research into public schools. In addition to our own workshops, we will be able to disseminate information to educators and administrators through our partnership with Jensen Learning Corporation. Jensen Learning Corporation is a professional training organization founded by Diane & Eric Jensen. Eric Jensen is the author of Brain-Based Learning and SuperTeaching and was amongst the first to suggest that educators should teach according to the ways in which brains learn best. Through the “Brain Learning Expo” events and special workshops, Jensen Learning Corporation teaches hundreds of teachers about the role of the brain in learning. The science of learning is a dynamic field, such that it is nearly impossible to stay abreast of current research. Thus, Eric Jensen is very excited to join our Center as a corporate sponsor. Through our partnership with Jensen Learning Corporation, the scientists in our research networks will team up to present our findings to educators and translate the applicability to educating America’s youth in a “brain-appropriate” manner. This partnership will allow us to reach 100’s of teachers across the nation, each year. Given that researchers are typically paid to speak at these conferences, Eric Jensen is willing to let us volunteer our services in exchange for teacher scholarships. Thus, a select group of teachers will be eligible for scholarships and free continuing
education credits. Additionally, Eric Jensen will be included in our all-center meetings, in order to aid his continued education regarding the science of learning.

Mechanisms for Training Undergraduate Students First, we continue our strong commitment to directly involving undergraduates in our research labs. Second, we will establish a Summer Undergraduate Science of Learning Institute to bring talented undergraduate students to UCSD for a month of intensive exposure to research (we may also establish a Winter Institute to accommodate students from universities with a January intersession period, such as Oberlin or Cornell). We will benefit from the recent experience of one of our partner institutions, Vanderbilt University, hosting the APA Summer Science Institute for undergraduates (http://www.apa.org/science/ssi.html).

Mechanisms for Training Graduate Students and Postdoctoral Fellows We will establish a “Ph.D Plus” program in the Learning Sciences, aimed at students in Cognitive Science, Computer Science and Engineering, Psychology, and Neuroscience. A major objective of this program is to assure that students will work with center faculty so as to gain a balanced coverage of experimental approaches in behavior or neuroscience and computational approaches to modeling the dynamics of learning in behavior or in the brain. Most students will have a strong background in one representative discipline. Our goal will be to broaden their training to include methods from outside their home discipline. We will do this through a variety of techniques, including dinner seminars, interdisciplinary team-taught courses, and “boot camps”. For example, our very successful boot camp approach has been applied in our NSF-sponsored IGERT in Computational Neuroscience and Vision and Learning in Humans and Machines. The Vision and Learning boot camp is a two week event providing intensive cross-disciplinary training and includes a significant project component. Student have been extremely enthusiastic about their boot camp experience. In addition, we will require students to do lab rotations outside their home departments and we will develop interdisciplinary team-taught courses to encourage both students and center faculty to learn each other’s vocabulary.

For postdoctoral fellows and selected graduate students, we will especially encourage lab visits between universities. In particular, we will encourage “bridge postdocs” who spend a year in one lab of a research network and another year in another lab, possibly at another location. This cements relations within the network and transfers techniques and knowledge from one lab to another. Unlike graduate students, it is impossible to prescribe a set training model for postdoctoral fellows. Instead, the details of the training program for each postdoctoral fellow are determined by the Independent Development Plan (IDP). Soon after arriving, postdoctoral trainees will be required to complete an IDP in consultation with their faculty mentor. This process is modeled after one outlined by the Federation of American Societies for Experimental Biology (FASEB) and involves four major steps: (1) a self-assessment of strengths and areas for development, (2) a mentored assessment of ways to meet research and career opportunities through courses, workshops, and research opportunities, (3) using the self and mentored assessments to write an IDP, which would include specific actions and a timeline for completing those actions, and (4) submission and implementation of the IDP, which will be viewed as a “work in progress” to be adjusted as needed.

Mechanisms for Training Researchers We will invite researchers from outside UCSD and our partner institutions to come to the Center for extended stays. We will also extend invitations to senior researchers to attend modified versions of our Boot camp. This will extend the boot camp concept to be aimed at both postdoctoral researchers and senior scientists who want to re-tool. We will develop focused boot camps on special topics, such as Computational modeling, Brain imaging, Slice preparations, and the Statistics of Interaction.

Mechanisms for Reaching the Public: The Science Network (TSN) We propose a unique outreach element: the use of media to document and help make more transparent the dynamics of the research/learning environment. We believe there are inadequate interfaces between the key players in the enterprise: scientific researchers, parents, teachers, and - of course - students. In particular, the conversation between researchers working in cognitive neuroscience and teachers delivering information to student minds is, unfortunately,
limited. We intend to draw on the expertise of a number of partners skilled in these areas to increase the traffic in ideas and the implementation of novel learning technologies. One proposed partner in this effort is The Science Network (TSN).

TSN is a visionary venture by a coalition of world-renowned scientists and media professionals to build a multi-media programming platform that will be a trusted destination for those concerned with science and its impact on society. Part of its core mission is to provide unfiltered discussion of science issues that intersect with social policy - a kind of C-SPAN for science, free from the tyranny of the sound bite.

In October 2004, as a proof of concept, TSN created a symposium at the Salk Institute, La Jolla. “Stem Cells: Science, Ethics and Politics at the Crossroads” was videotaped and the symposium, entire and unedited, was streamed live on the TSN website. Later, three individual programs, on the Science, the Ethics, and the Economics and Politics of Stem Cell research, were broadcast nationally on the University of California TV Network twenty-eight times during October, prior to the election and the voting on California proposition 71, thus fulfilling our aim of delivering gold standard information on issues at the intersection of science and public policy.

In 2005, TSN has videotaped additional symposia on “The Legacy of Einstein’s Science” (in partnership with the American Friends of the Hebrew University, Jerusalem); and a second Stem Cell Forum on “Regulatory and Ethical Issues on the Use of Stem Cells: An International Perspective”, as part of the Days of Molecular Medicine (DMM) 2005 meeting (in partnership with UCSD, The Salk Institute, and the journal Nature Medicine). TSN has been invited to participate in DMM 2006 at the Karolinska Institute, Sweden. TSN has also co-organized and videotaped a symposium on “Brains, Minds, Consciousness” at the California Institute of Technology; and collaborated with the Public Policy Institute at Georgetown University in the videotaping of a symposium on “Preparing for the Inevitable: Bioterrorism and Emerging Infectious Diseases” at the Library of Congress. Future events include the SENS2 Gerontology meeting at Cambridge University (UK); and the Keystone Symposium on “Stem Cells, Senescence and Cancer”, sponsored by the Agency for Science, Technology and Research (A*STAR) in Singapore.

The Science Network has recently received a major grant from the Dana Foundation to produce a series “Scientists on Science” (working title), a living archive of interviews with leading scientists, accessible to a general audience – particularly young people. Additional funding to date has been received from numerous sources including The Swartz Foundation, The Kisco Foundation, The Salk Institute, The Kavli Foundation for Brain and Mind at UCSD, and the Andrew and Erna Viterbi Family Foundation.

The vexing issue of devising an optimal learning environment - based on a pedagogical technology that would be efficient, economical, enlightening and exhilarating - sits precisely at the intersection of science and social policy. What could be of more concern to parents than that their children - our investment in the future - should be well schooled? In an ideal world, the dynamics of the learning environment should consist of ongoing interactions (with feedback) between children in classrooms and teachers; between teachers, principals and district superintendents; between children and parents; and between parents and teachers. Scientific researchers should, in theory, be mining data from this dynamic learning environment (and, at a more fine-grained level, from individual brains using EEG and fMRI), and feeding their results back into the educational system. In practice, this happens too infrequently.

One model system already developed by Scientific Learning Corporation (SLC), one of our partners in the Education Outreach Center, uses technology more optimally to create a more dynamic learning environment. The newly released Gateway Edition of SLC’s Fast ForWord series of neuroplasticity based educational intervention programs, based on over 30 years of laboratory research, collects secured data, mouse click by mouse click, on each student’s progression through a series of individualized interventions. These data are uploaded daily over the Internet to SLC and electronically scored, with learning progressions graphed, per student, per classroom or per school for use by parents, teachers, principals or district superintendent. In addition to being a monitoring system, this “smart system” also adapts the intervention to each student’s needs, flags teachers as to how to best intervene for each student, when needed, to optimize their learning trajectories and outcomes, and flags principals and district school superintendents as to levels of protocol compliance and completion for individual students, classrooms and schools. The system also provides a means of uploading test and assessment data on each student at various time intervals and helps schools predict which students need more intervention to reach mandated No Child Left Behind
Adequate Yearly Progress requirements. Through collaboration with research scientists, and appropriate IRB approvals, this system could be used to integrate additional fine-grained individualized data (including electrophysiological and imaging data) for future research studies on the dynamics of learning. As the system is currently in use at over 2000 schools nationwide, this partnership with Scientific Learning Corporation through the Educational Outreach Center of this grant provides the potential to mount a “real world” laboratory to explore the dynamics of leaning across multiple dimensions in classrooms nationwide.

There is tremendous public as well as educational interest in normal as well as abnormal brain development, normative milestones and how developmental cognitive skills underlie the major subjects of interest to schools, especially language development, literacy, math, social development. During the first year of the Center’s operation, TSN in collaboration with our other partners in the Education Outreach Center, will plan and produce a symposium on this area, bringing together all of the stake-holders, parents, students, teachers, school administrators, scientists, professors at teacher’s colleges, education business leaders and public policy makers to discuss the crisis in US education and its implications on our future economic competitiveness internationally.

Several of The Science Network program formats in production (and in development) could document the impact of the Center and make available advance to a wide range of teachers, parents, students and anyone else that is interested in education. Specifically, we have in mind a program documenting the trajectory of the interaction between researchers and their “subjects” (parents, teachers, students) as feedback is increasingly introduced into the system. A town hall meeting or symposium on this subject would also be valuable. And, finally, the very visible presence of a TSN bus/studio would be a tremendous traveling focus of attention. TSN could, in this fashion, quite rapidly generate a community of the concerned.

Scientific Learning Corporation already has a very active website (see www.brainconnection.com). Brain Connection was designed specifically to provide for a more rapid transfer of information between scientists and educators interested in how the brain learns. As part of the Educational Outreach Center, grant participants will provide content for the Brain Connection website pertaining to scientific breakthroughs of specific interest to educators. This will provide a direct and rapid link between the scientific work or our center and its dissemination to educators.

During years two and three, programming on TSN and content on the Brain Connection website will be created that is more directly related to each of the modules that structure this grant. In years four and five, coverage will be extended to include the research and outreach at other Science of Learning Centers.

Development. During the first year of the Centers operation, TSN will plan and produce a symposium on this area, bringing together all of the stake-holders, parents, students, teachers, administrators, scientists, professors at teacher’s colleges, public policy makers to discuss the crisis in US education and its implications on our future economic competitiveness internationally. During years two and three, programming will be created that is more directly related to each of the modules that structure this grant. In years four and five, coverage will be extended to include the research and outreach at other Science of Learning Centers.

All programming formats will eventually be available on the TSN website (www.thescienceatenet.org) as streaming Video on Demand (VOD) and, in more bite- size edited versions, using the new technology of “podcasting”. This means that people anywhere, at any time, with the capability to download MP3 files will be able to listen to indexed capsule segments from the programs. In keeping with our commitment to fully utilize new technologies that enhance speed and interactivity, we plan to develop a mobile studio (similar to the bus used by C-SPAN Book TV) to take science more effectively to the wider community. Partnerships with PBS stations and local libraries, museums and science centers are also envisaged. We believe this leveraged outreach activity, together with the TSN web community, represents a unique added value in communicating science to the public that underwrites it.

All of the programming created by the Center will be available as VOD from the TSN web site and through links to the Center website and other web sites such as The Brain Connection: http://www.brainconnection.com/

The Center will use the Preuss school as an interactive living laboratory. Outreach from the Center will reach a wider world through three major conduits that are already in place: The Science Network (which will create original programming), The Brain Store and Jensen (organize workshops for teachers) and Scientific Learning Corp., which has experience with delivering software to classrooms, networking with educational decision makers and delivering for-credit web courses for teachers on issues pertaining to “How the Brain
Learns” through its educator website www.brainconnection.com.

5 Diversity Plan

The investigators in the Dynamic Learning Center are committed to the recruitment and training of individuals from underrepresented groups. A number of institutional and center strategies have been implemented or will be implemented to increase diversity in the center. In order to monitor the success of our efforts, we will appoint one of our senior investigators to be responsible for supervising efforts in recruiting individuals from underrepresented groups, collating data on the diversity of the center and its efforts to increase diversity, keeping center investigators aware of opportunities for outreach and recruitment possibilities, and maximizing the use of institutional programs aimed at increasing diversity of faculty, staff, and students.

Having minority faculty in the classroom and in the laboratory can have a major influence on encouraging our minority undergraduates to pursue advanced study and can significantly increase the recruitment and retention of minority graduate students. Our institutions have put in place programs aimed at recruiting and retaining faculty from underrepresented racial and ethnic groups. For example, Vanderbilt University has recently instituted a program for “Target of Opportunity Appointments” to allow a department to add entirely new faculty lines for minority faculty hires. Other institutions affiliated with the Center are making similar institutional commitments to faculty diversity. The Dynamic Learning Center has a number of world-class female faculty who will serve as role models to encourage young women to enter the sciences. We recognize that some areas represented in the Center, especially systems neuroscience, have far too few female faculty and we will encourage efforts by our institutions to promote gender equity.

We use a range of recruiting strategies to inform and educate undergraduate minority students about the possibilities and merits of careers in science. Direct mailings, local and national recruiting at career days, sponsorship in summer research program, and support for minority faculty recruiting are just some of the measures taken. We will send posters for the Dynamic Learning Center to psychology, education, and computer science departments on a broad list of institutions identified through the National Association for Equal Opportunity in Higher Education. But we will also introduce more active strategies aimed at increasing our diversity at the graduate level.

Involving high school students from underrepresented minorities is a great place to start in increasing undergraduate diversity in the science of learning. In a previous section, we described our partnerships with the Preuss school. 22% of the Preuss school graduates will be attending UCSD in the fall of 2005, from a population of students that is about 60% Hispanic and 13% African American. The female faculty in the Center will especially serve as role models to the female students in the Preuss school.

At UCSD, we will increase graduate student diversity with programs developed in cooperation with UCSD’s Office of Graduate Studies and Research (OGSR). We will model some of our efforts after a successful program established at UMD College Park, which resulted in UMD awarding 16% of their doctoral degrees to students of color. The main feature of the approach is called the Faculty Partners Program, a mechanism for faculty to develop personal relationships with faculty at predominantly minority-serving institutions. Research shows that the person who most influenced a student’s choice of graduate school is their faculty advisor at the undergraduate institution. Thus developing relationships with these faculty is crucial. The best way to build these relationships is through visits. One approach is for a center investigator to visit minority undergraduate institutions in order to present opportunities for research careers with center investigators to their students and faculty. Another approach is to bring faculty from predominantly minority-serving institutions to UCSD or another center institution for two days of presentations, laboratory tours, and other formal and informal meetings. In a similar program, Vanderbilt has established partnerships with Historically Black Colleges and Universities (HBCU’s), including Fisk, Tennessee State University, and the University of the Virgin Islands. Members of our faculty visit HBCU’s to meet with faculty and students, talking about careers in the sciences generally and opportunities at Vanderbilt specifically. In addition, we have established a program whereby Vanderbilt faculty teach introductory courses at Fisk, a neighboring HBCU. Vanderbilt faculty have also brought Fisk students into our laboratories for summer internships. The institutions of other center investigators have established their own programs of this sort to increase diversity at the graduate level. The Dynamic Learning Center will support all costs associated with traveling
to minority-serving institutions, bringing faculty from minority-serving institutions to center sites for visits, and supporting summer research internships for undergraduates from underrepresented minorities.

OGSR at UCSD also operates several traditional preparation programs to attract underrepresented UCSD undergraduates into graduate school by involving them in university research activities. The NSF MASEM program (of which the PI is a Board member), the NIH MBRS/IMSD program, the CSU Pre-doctoral Fellowship Program, and the UC LEADS program all target underrepresented undergraduate students for eight-week summer research internships. Students are provided research training, exposure to graduate students and faculty, and workshops on GRE preparation, public speaking, application preparation, and graduate school preparation. Our partner institutions offer similar programs, funded internally or externally, to bring promising minority undergraduates into careers in the sciences.

To increase recruitment of graduate students from underrepresented minorities, UCSD and partner institutions offer a variety of programs to maximize the likelihood of these individuals enrolling in our graduate programs. OGSR at UCSD has promised to dedicate two two-year UCSD Diversity Fellowships each year to our program. The Office of Diversity and Equity at Colorado has created CU-LEAD (Leadership, Excellence, Achievement, and Diversity) Alliance, which provides academic support and scholarships for students of color and first-generation students. Vanderbilt offers graduate fellowships to graduate students from underrepresented minorities and individuals from economically disadvantaged groups. Other institutions offer similar programs aimed at recruiting excellent minority students into our graduate programs.

To increase the retention of graduate students from underrepresented minorities, we will create and support a program of peer mentoring, where students will be mentored by more senior students of color. We will encourage participation in student associations, and will develop mechanisms for faculty and students of color to bond, such as student-faculty lunches and other events. Our institutions have set up excellent support offices to help ensure the success of our minority students in their graduate careers. The center will facilitate those efforts already in place. In addition, the Center will promote mentoring programs for women in the Science of Learning at all levels, from undergraduate and graduate students, to postdoctoral fellows, to junior faculty.

6 Management Plan

The Executive Committee of the Dynamic Learning Center will consist of the PI (Gary Cottrell), the co-PI’s on the UCSD core (Andrea Chiba, Daniel Feldman, Javier Movellan, and Terry Sejnowski), co-PI’s on the Perceptual Expertise Network subcontract (Isabel Gauthier and Thomas Palmeri), and the co-Directors of the Education and Outreach Resource (Paula Tallal). We will also invite a senior graduate student or a postdoctoral fellow to serve on the Executive committee. The day-to-day operations of the center will be led by the PI (25% academic year support, one month summer support), aided by a Management Services Officer and a Budget Administrator. Cottrell will also be the key contact with NSF and the Directors of other NSF Science of Learning Centers. The day-to-day operations of the individual Research Networks will be led by co-PIs (one month summer support each): Chiba (Interacting Memory Systems); Feldman (Sensorimotor); Gauthier and Palmeri (Perceptual Expertise); and Movellan (Social Dynamics). The day-to-day operations of the Education and Outreach Resource will be directed by Sejnowski and Tallal (two months summer support). The Cross-Cutting Resources will be headed by Mark Appelbaum (The Data Sharing Grid), Scott Makeig (The Spatio-Temporal Dynamics Laboratory), and the California Institute for Telecommunications and Information Technology (The Motion Capture Facility). Administration of the Dynamic Learning Center will be supported by a full-time Project Coordinator, a full-time Administrative Assistant, and a half-time Budget Officer. We have also obtained commitments from the California Institute for Telecommunications and Information Technology (Calit2) to supply the services of personnel to develop and maintain the Center web pages.

The Executive Committee will oversee the distribution and utilization of research funds in the four Research Networks, the Education and Outreach Resource, and the three Cross-Cutting Research Resources. It will make final decisions regarding major education and outreach activities of the center. It will oversee the organization of annual center meetings. It will oversee the organization of summer workshops for teachers and for scientists. It will evaluate how well the center is achieving its goals for diversity through the inclusion
of men and women, underrepresented minorities, and persons with disabilities in center activities. It will evaluate how well the center is achieving its goals for the training and placement of graduate students and postdoctoral fellows. It will evaluate how well the individual networks are achieving the broad center goal of building dense interconnections of collaborations within each network and across networks. It will appoint center members to serve as liaisons to other NSF Science of Learning Centers to develop partnerships on shared scientific, education, and outreach activities. The Executive Committee will turn to its external Advisory Committee for an independent evaluation of how well the Dynamic Learning Center is achieving its research, training, education, and outreach goals, and to provide guidance for adjusting center priorities in order to address important scientific, education, workforce, and national security priorities.

We have recruited a diverse international group of leading experts in the science of learning to serve on our external Advisory Committee: Sue Becker (McMaster University), Peter Dayan (University College London), Robert Goldstone (Indiana University), Annette Karmiloff-Smith (University College London), Mark Mayford (The Scripps Research Institute), James McClelland (Carnegie Mellon University), Janet Metcalfe (Columbia University), Alcino Silva (University of California), Wolf Singer (Max Planck Institute for Brain Research, Frankfurt), Los Angeles), and Richard Sutton (University of Alberta). The Advisory Committee will meet once per year to fully review the research, education, and outreach activities of the center and to make recommendations for places of further investment, divestment, or changes in priorities. We will schedule our Annual Center Meeting to coincide with the Annual Advisory Committee meeting in order to maximize opportunities for members of the Committee to see the outcomes of our center first hand. During our first year, we will work closely with the Advisory Committee to establish the rubrics to be used for evaluating and assessing the center. The main goal of the Advisory Committee will then be to serve as a third party evaluator to review the progress, direction, and leadership of the center.

As detailed earlier in the Education and Outreach plan, the co-Directors of the Education and Outreach Resource (Sejnowski and Tallal) will coordinate outreach activities with local schools (The Preuss School as an interactive living laboratory), schoolchildren (through partnership with Reach For Tomorrow bringing underprivileged high school students in contact with the sciences), industry partners in teacher training (The Brain Store and Jensen Corporation), industry partners in educational software development (Scientific Learning Corporation), and The Science Network. A half-time professional Outreach Coordinator (Michael Dabney), whose remaining effort is devoted to other aspects of Outreach at UCSD, will work closely with Sejnowski, Tallal, and the center co-PI's to maximize the effectiveness of our Education and Outreach efforts. Collaborators and colleagues at our institutions and industry partners have also offered to consult on important aspects of the education and outreach activities of the center. Andy Porter, the Director of the Vanderbilt Learning Science Institute, will consult on important aspects of outreach linking basic research on the science of learning with educational policy and practices. Roger Bingham, Director of The Science Network, will consult on effective ways of communicating science and its implications for education and practice to the public.

Title to any invention, development, or discovery arising under this center (Invention) shall be determined in accordance with United States Patent Law; Title 35 United States Code. Any Invention, which is made exclusively by an employee of either University or any other project participants, shall be solely owned by the respective inventing party. Any Invention, which is made in part by an employee of both University and participants, shall be jointly owned by the parties. Any technology developed under the project shall be licensed or otherwise managed in accordance with the policies of the technology owner and in accordance with NSF policy. Determinations regarding ownership of software and its commercial use will be made in accordance with the policies of NSF, US Copyright laws and the individual participants.

7 Evaluation and Assessment

Evaluating Our Center: The assessment of the Center will involve several components. First, the Executive Committee will conduct a self-assessment. To facilitate this assessment, as well as to facilitate shared knowledge within the group, we will have an annual All-Center Workshop in which we report on our basic research findings as well as the results of our Outreach components. We plan this to be a two-day single-track meeting. Each Research Network will present an overview of their scientific results. We will share
information concerning the best practices we have discovered in our Cross-Cutting Components; this is especially the case for the Data Sharing Grid, which we feel will be an innovative tool for promoting access to data, and could form a prototype for other Centers. The Education/Outreach Center will report on the results of work with the Preuss School, the Teacher Boot Camp, and the Academic Boot Camp. The Executive Committee will use the outcomes from the annual meeting along with reports from the Networks and Cross-Cutting Components to highlight our successes and failures with respect to meeting the goals of the Center.

Second, and more critically, we will obtain an independent third party evaluation of our Center from the external Advisory Committee. We expect members of the Advisory Committee to attend the annual All-Center Workshops to help them assess the progress of the Center from year to year. In addition to attending the the annual meeting, we will also provide the Advisory Committee with reports on our publications and other research activities, feedback from teachers at Preuss and the Early Childhood Education Center, feedback from participants in the boot camps, as well as feedback from the students, postdocs, and visitors to the meetings. The Perceptual Expertise Network has already developed feedback forms for the academic personnel involved in their Network that we can use as a model. In the first year on the Center, the Executive Committee will work together with the Advisory Committee to establish rubrics by which the Center will be evaluated. After the first year, the Executive Committee will use these rubrics to critically review the progress, direction, and leadership of the center, providing us with formative and summative evaluations.

Evaluating Our Science: We will establish rubrics for evaluation of the science that we develop. The Center will be successful if we create collaborative teams of researchers approaching the issue of the temporal dynamics of learning from multiple perspectives. Using success of the organizing principles of the Perceptual Expertise Network (PEN) as a proof of concept, we aim to create a new paradigm for research that involves synchronizing disparate research methodologies around common questions. We expect this process to create conceptual collisions between researchers from different disciplines, causing a new synthesis from old parts. While precisely quantifying how well we achieve such lofty goals is difficult, documenting the number of individual publications, collaborative publications, and complementary research grants, has proved a useful metric for evaluating the previous success of PEN. We will also require each Network to submit a yearly progress report on activities, documenting publications, complementary grant funding, awards, and other notable Network results.

Evaluating Our Training: The Center will be successful if we train a next generation of scientists who do world class research, driven by important questions not techniques, who see collaboration with individuals from disparate perspectives as an opportunity rather than a challenge, and who strive to connect their research to education, workforce, and national security challenges. Some obvious ways of quantifying our success in training is by productivity in research and by placement in top tier universities. However, we have also found that feedback forms from the students and postdoctoral fellows involved in the PEN network has allowed us to be able to modify our meeting formats and interactions in important ways.

Evaluating Our Education and Outreach: The Center will be successful if the Educational Outreach Center develops a bi-directional approach, with not only the science being transmitted to educators and the public, but also our interaction with educators and the public having a direct impact on adapting the questions we ask scientifically to better meet the needs of our educational stakeholders. For example, we will not only create programming through The Science Network for the public, but we will learn from public response to these programs what information is of most relevance to them and use this input to develop future programming. Similarly, we will not only provide information to educators derived from our mutual interest in the dynamics of learning, but we will also learn from our close interactions with educators and their students what issues are most in need of future research. Our interactions with our corporate partners will also be a two way street. For example, Center scientists will be able to provide these partners with rigorous scientific content for their websites and speakers for their conferences directed at K-12 educators specifically interested in how the brain learns. Our corporate partners, in return, will be able to provide us with much more direct, personal interactions with the major education leaders with whom they interact with on a daily basis. We will know that we are successful if these reiterative interactions from the science to education outreach and back to the science lead to much more rapid translation of our research into practical application in the classroom, and data taken directly from student’s learning in the classroom becomes
rapidly integrated into our research.

Evaluating Our Investments in Resources: The Center will be successful if we invest in the kinds of cross-cutting tools that significantly maximize the quality and the impact of our science. We will monitor the activities in each of the Cross-Cutting Resources in order to invest or divest in resources according to their impact. In addition, we will set up mechanisms for Center investigators to recommend investments in new cross-cutting resources as well as refining the ones we have proposed here.

8 Facilities, Equipment, and Other Resources

UCSD has committed to providing a suite of offices for the core unit of the Dynamic Learning Center within a new building that will be completed this summer. This suite will house administrative offices, a conference room with state-of-the-art audio-visual and networking capabilities for center meetings, additional office space for predoctoral and postdoctoral trainees, offices for visiting scholars and off-site center investigators. This new building will also have facilities for hosting the boot camps, institutes, summer teacher workshops, research camps, and large center meetings. Support has also been secured for our Cross-Cutting Resources: The San Diego Supercomputer Center will provide support and expertise for the Data Sharing Grid, the UCSD Center for FMRI will supply space and resources to support the Spatio-Temporal Brain Dynamics Facility, and space has been secured to support the Motion Capture Facilities.

UCSD and its partner institutions (Vanderbilt, The Salk Institute, Colorado, Yale, Brown, Berkeley, Carnegie Mellon, Victoria, Rutgers, Pittsburgh, Queensland), have provided our investigators with excellent laboratory facilities, state-of-the-art equipment, and access to unique resources needed for the research described in the proposal. All investigators have offices and ample laboratory space provided by their institution for studies with humans, children, animals, and computational models. Laboratories include specially configured space for electrophysiological recording, animal surgery, histology, behavioral experiments, audiovisual recording, patient testing, child testing, and the like. All investigators have numerous desktop computers, laptop computers, and high-end computer workstations in their laboratories and offices for data analysis, stimulus generation, experimental control, and computational modeling. Investigators also have access to high-performance computing facilities such as the ACCRE Beowulf cluster at Vanderbilt, the Beowulf computational cluster at Carnegie Mellon, and the San Diego Supercomputer Center (SDSC). Institutions have machine shops, electronics shops, graphical design facilities, and other shared resources to facilitate research. Institutions have established human subject pools to facilitate laboratory experiments on human learning. Institutions supply generous support for administrative assistants and technical secretaries to support research activities. Institutions have also made significant investments in the science of learning through faculty appointments, increased graduate student support, and the creation of other university centers to support research of learning in humans, animals, and machines. As outlined in more detail in the Facilities pages, we have access to world-class resources for doing brain imaging, electrophysiology, neurophysiology, developmental studies, computational modeling, and other cutting edge research on the science of human learning.

As discussed in the Education and Outreach section, we have secured partnerships with The Preuss School to be an interactive living laboratory, Reach For Tomorrow to bring underprivileged high school students in contact with the sciences, The Brain Store and Jensen Corporation to partner in teaching teachers about the science of human learning, Scientific Learning Corporation to partner in creating software for education and treatment, and The Science Network to bring the science of learning to the greater public.

9 Sustainability

UCSD, Vanderbilt, Colorado, and all of the other core institutional components of the Dynamic Learning Center have made major investments in the science of learning in recent years and there is no expectation that these commitments will diminish in the coming years. UCSD has just inaugurated the Kavli Brain and Mind Institute, headed by Jeff Elman and Nick Spitzer. The Computer Science Department has just hired Yoav Freund, a major figure in Machine Learning (winner of the Goedel Prize and inventor of AdaBoost, the
most effective new machine learning algorithm in the last ten years), and has plans to hire additional faculty in Machine Learning. UCSD is also committed to providing staffing for the Center beyond the period of the grant and has committed significant space to support the Center’s activities. UCSD is also committed to diversity, providing 2 diversity fellowships per year to the center. Vanderbilt has made major investments in the science of learning through the creation of the Learning Sciences Institute (Andy Porter, Director), the Center for Cognitive and Integrative Neuroscience (Jeffrey Schall, Director), and the Institute for Imaging Sciences (John Gore, Director). Vanderbilt has also invested heavily in graduate education, guaranteeing support for students for five years, and has launched significant new investments in reinventing graduate education.

The investments made by this center will continue long after NSF support ends. Should the aim of becoming the CSPAN for science be realized, our significant outreach investments in The Science Network will continue to reap rewards for years after the center funding ends. Our model for training graduate students in collaborative research networks will be sustained as a standard component of our graduate programs in the future. The dominant presence of the Dynamic Learning Center will attract new colleagues in the science of learning to our institutions, ensuring that investments in the science of learning at our institutions will continue for years to come. The collaborative research networks developed through support of this center will ultimately be sustained by research grants from NSF, NIH, and other institutions and foundations, continuing to push the envelope of science for decades to come. Ultimately, we see our elaboration of the PEN model of collaborative research becoming the standard model for doing science, guaranteeing sustainability of our vision for research in the years to come.