The Temporal Dynamics of Learning Center

An NSF-funded Science of Learning Center

Strategic and Implementation Plan
Year One
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SECTION I

Purpose

To achieve an integrated understanding of the role of time and timing in learning, across multiple scales, brain systems, and social systems, to 1) create a new science of the temporal dynamics of learning; 2) to use this understanding to transform educational practice; and 3) to create a new collaborative research structure, the network of networks, to transform the practice of science.

Mission statement

The Dynamic Learning Center is a multi-institution group of scientists and educators focused on understanding the critical role of time and timing in learning. The Center investigators comprise four interacting research networks, providing strong expertise in each of four fundamental areas of learning: sensorimotor learning, brain memory systems, learning of expertise, and social interactions related to learning. In addition, the center has cross-cutting resources representing innovative technologies to support learning research and data sharing. The Center will recruit the most relevant investigators and technologies to each research network to form a diverse interdisciplinary group of scientists to address major, unanswered research questions central to the temporal dynamics of learning. Examples of research questions include: How is temporal information about the world learned? How do the intrinsic temporal dynamic properties of brain cells and circuits facilitate and/or constrain learning? How can the temporal features of learning be used to enhance education? What are the best theoretical ways to conceive the temporal dynamics of learning in the brain and between brains? Each research question will be selected to be highly interdisciplinary, to cross the boundaries of traditional fields of learning research, and will be informed by interactions with educators.

This will lead to development of novel, highly cross-disciplinary answers and theories for each question. As answers become well developed, ideas and technology will be translated via specific education and outreach efforts to a diverse set of K-12 students, educators, undergraduate and graduate students, and to other stakeholders with support from our corporate partners and The Science Network, a C-SPAN for science. While advancing our science, the center will also promote a new type of collaborative scientific research paradigm in the form of a network of research networks structure.
Rationale for the Center’s Research Initiatives

Introduction

It is commonly accepted that there is a crisis in education in the US. We have too many struggling learners, too many students who drop out before finishing high school, too many students who cannot read, too many students who cannot do basic arithmetic, let alone advanced mathematics. What is not commonly accepted is what to do about this crisis. In spite of the No Child Left Behind Act, in spite of increasing funds being allocated to improve reading, reading scores remain flat. We believe that part of the current crisis in education is the lack of scientific understanding of how the brain learns, and the lack of translation of this scientific understanding to the classroom. An essential understudied component of learning that could have a strong impact on education is the role of time and timing in learning.

Why timing? Because timing is critical for learning at every level, from learning the precise temporal patterns of speech sounds, to learning appropriate sequences of movements, to optimal training and instructional schedules for learning, to interpreting the streams of social signals that reinforce learning in the classroom. Moreover, a decade of neuroscience research demonstrates that the intrinsic temporal dynamics of processes within the brain also reinforce and constrain learning. For example, we have discovered that slow learners tend to have slow “shutter speeds” in terms of how their brains take in and process information. The underlying problem for at least some poor readers is the their inability to perceive fast acoustic changes in speech sounds (phonemes) that must be accurately perceived in order to learn letter–sound correspondence rules for reading. Neuroscience-based training regimes that improve this temporal processing ability improve both spoken and written language learning in struggling readers (for review see Tallal, 2004).

From this and other successful examples, we believe that by investigating the temporal dynamics of learning we can change the capacity of children to learn, as well as change the environment to aid in learning.

The scientific goal of the center is therefore to understand the temporal dynamics of learning, and to apply this understanding to improve educational practice. This goal requires a broad, multi-disciplinary research approach, with strong integration of research findings across levels of analysis. A multi-disciplinary approach is required because learning occurs at many levels: at the level of synapses and neurons; at the level of brain systems involved in memory and reward; at the level of complex motor behaviors; at the level of expertise learning; and finally, at the level of learning via social interactions between teachers and students. Each level has its own temporal dynamics, and its own timing constraints that affect learning. Of course, these levels are not independent, but instead, timing constraints at one level affect learning at another level in a nested way. For example, the dynamics at the cellular level, which is often on the order of milliseconds, implement learning on the whole-brain and behavioral level on much longer time scales, including memories that last a lifetime. Our goal is to use a multidisciplinary approach incorporating cellular and systems neuroscience, cognitive science, brain imaging, study of human social interactions during learning, and learning theory to study temporal dynamics of learning over the broadest possible range of levels, both temporal and spatial, from cells to social
interactions, and from milliseconds to years. We believe that an enterprise of this scale requires
the Center mode of organization.

In order to address questions of such broad scope, we have created four research networks, each
of which focuses on a different, major aspect of learning: sensorimotor learning, memory,
perceptual expertise, and social systems related to learning. Each network is composed of
multiple principal investigators who bring complementary techniques, disciplinary perspectives,
and expertise to the network. The Sensorimotor Network (led by Dan Feldman, UCSD) studies
relatively simple forms of sensory learning (e.g., speech perception) and motor learning,
focusing on brain mechanisms for learning at the single-neuron and circuit level, and
computational strategies of learning. The Perceptual Expertise Network (led by Thomas Palmeri
and Isabel Gauthier, Vanderbilt University) studies the dynamics by which people acquire
expertise in identifying and interpreting objects in the world (e.g., common expertise for
recognizing faces or letters, and specialized expertise for reading X-rays or screening luggage).
The Interacting Memory Systems Network (led by Andrea Chiba, UCSD) studies learning of
complex associative and episodic memories, focusing on how different brain systems code these
memories with different temporal requirements. The Social Interaction Network (led by Javier
Movellan, UCSD) explores the social interactions that provide the context for much of learning.
This network studies how the brain addresses the timing constraints and computational demands
of real-time social interactions, and how these features of social interaction affect the learning
process. All networks incorporate both experimental researchers and computational modelers,
who will work within and across networks to develop integrated theoretical and conceptual
understanding of learning processes. Most of the science of the Center will be conducted within
the context of the research networks. The research networks will have regular “Network
Meetings” to share ongoing research, coordinate collaborative projects, and plan new
collaborations.

Research in the Center will be organized around four specific Center Initiatives that define an
emerging Science of the Temporal Dynamics of Learning. The scientific goals of each initiative
are inherently cross-disciplinary, and will require coordinated research by all four research
networks. Thus, the members of the research networks associated with each initiative will also
meet together on a regular basis in “Initiative Meetings” to synchronize their research around
these Center Initiatives. This combination of Initiative Meetings and Network Meetings
represents a combined vertical integration of science, where scientists build working
relationships and share ideas related to the broad, conceptually-oriented Initiatives; and
horizontal integration in which scientists develop deep technical expertise by working with other
labs examining the same fundamental aspects of learning using a diverse, yet synchronized, array
of methods, techniques, and levels of analysis. In this way, we will achieve an integration of our
science that is not possible within one research initiative or one research network. It is through
this mechanism that the whole will produce more than the sum of its parts – the networks and the
initiatives will be interdigitated to create a seamless web of the new science of the temporal
dynamics of learning.

In addition to these research initiatives, we will also develop four cross-cutting resources to
further integrate and facilitate scientific inquiry across the center: 1) The Data Sharing Facility,
led by Reagan Moore and Mark Appelbaum, will enable Center participants to share, analyze,
compare, and mine data; 2) The *Motion Capture Facility*, led by Emo Todorov and Howard Poizner, will enable research investigating the fine-scale dynamics of movement for the study of learning in motor control and to investigate the dynamics of social interactions in teacher/pupil settings; 3) the *Brain Dynamics Facility*, led by Scott Makeig, will develop the technology to assess ongoing brain activity during interactions between people, to acquire temporal and spatial data simultaneously from EEG embedded in fMRI; and 4) the *Education and Outreach Center*, led by Terry Sejnowski and Paula Tallal, will provide the interface between our science and the educational technology industry, teachers and administrators through our corporate partners Jensen Learning Corporation and Scientific Learning Corporation, and finally, the public and policy makers through The Science Network, a C-SPAN for science.

The Education and Outreach Center will also foster our partnerships with educational institutions: the Preuss School, an innovative, UCSD-sponsored charter school that sends nearly 100% of its highly diverse student body to college, and the UCSD Early Childhood Education Center, a preschool where our social robot, RUBI, teaches toddlers their colors and shapes. We intend that by using these institutions as testbeds for educational technology that arises from our research, we can quickly learn what works and what doesn’t work. Furthermore, we will involve the teachers from these institutions to help guide our research towards what is actually needed in the schools. Through this process of “inreach,” we hope to avoid ivory tower research that has little impact on educational practice.

This 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. Our corporate partnerships will allow us to engage in an ongoing dialogue with tens of thousands of K-12 school teachers and administrators through their websites, newsletters, national workshops and courses, making cutting-edge research and basic neuroscience available to educators on an ongoing basis for the purpose of updating educational practices to reflect our new knowledge of the temporal dynamics of learning. Conversely, these “outreach” mechanisms will also allow “inreach” from K-12 educators back to scientists, allowing teachers to educate scientists regarding issues of importance to “real-world” classroom learning. Our partnership with The Science Network will make our research available to a broad sector of the population.

**Center Initiatives**

Our goal is to create a science of the temporal dynamics of learning. A coherent view of temporal dynamics relating to learning does not currently exist. In addition, it is difficult to predict which aspects of learning dynamics will prove the most relevant for improving education. Thus, we chose to identify as our Center Initiatives four broad but critical questions that logically parse the temporal dynamics of learning into its constituent components. The value of this approach is that answering the Initiative questions would, in itself, constitute a somewhat complete science of temporal dynamics of learning.
The selection of Initiatives is based on the idea that there are four sources of temporal dynamics for learning: (1) Dynamics in the external world (including sensory stimuli, interpersonal interactions, and rewards). Some of these dynamics are explicitly learned, for example sequence and order of speech sounds and other sensory inputs. Others influence learning, such as the relative timing between action and reward. (2) Dynamics intrinsic to the brain itself (e.g., cellular processes within neurons, or activity patterns in brain networks, such as oscillations) and dynamics that have been shaped by development and experience. These dynamics can influence how and what the brain learns. (3) Dynamics of the muscles and body. These are learned to enable appropriate movements, and also to allow active movement of sensors like eyes, fingertips, and the body, to sample the environment. (4) Dynamics of learning itself (e.g., the rate and duration of learning). These determine how fast different forms of learning occur, and how long they last.

Thus, our four Center Research Initiatives are:

1. TEMPORAL DYNAMICS OF THE WORLD: How is temporal information about the world learned and how do the temporal dynamics of the world influence learning?
2. TEMPORAL DYNAMICS OF THE BRAIN: What are the temporal dynamics of brain cells, brain systems, and behavior? How do these dynamics change with learning, and how do they influence learning?
3. TEMPORAL DYNAMICS OF MOVEMENT AND EXPLORATION: What are the temporal structures for body movements and sampling the environment and how are they learned?
4. TEMPORAL DYNAMICS OF LEARNING: What mechanisms determine the time course of learning itself and what general principles explain the dynamics of learning across multiple scales and domains?

Each of these broad Center Research Initiatives will be addressed by formulating specific research strands that represent concrete, approachable, answerable research questions on subtopics within the initiative. The Center will focus on one or a few strands within each initiative at any given time; over time, completion of multiple strands within each Initiative will allow meaningful answers to the Initiative questions to be formulated. Strands prioritized for initial study will be detailed in the implementation section of this document.

In addition, we have four Center Integration Initiatives that are not directly scientific investigations, but will aid the development of the science:

5. Development of technologies for the science of learning
6. Integration of research and education
7. Diversity
8. Implementing, documenting, disseminating, and evaluating the Network of Networks paradigm for scientific inquiry

In the following pages we elaborate upon these eight initiatives. For the research initiatives, we also discuss examples of research strands that will directly address the questions put forth by our initiatives.
SECTION II: An Overview of the Center’s Eight Initiatives

INITIATIVE 1. TEMPORAL DYNAMICS OF THE WORLD: How is temporal information about the world learned and how do the temporal dynamics of the world influence learning?
(Initiative Coordinators: Dan Feldman and Paula Tallal)

The external world around us is not static, but is rich with temporal patterns on time scales ranging from milliseconds to seconds to minutes and longer, that convey critical information for sensation, communication, and survival. A fundamental aspect of learning is to implicitly or explicitly learn these behaviorally relevant temporal patterns, to guide perception and behavior. For example, in speech perception, infants learn to parse a continually varying stream of speech into basic speech sounds (phonemes) by learning to recognize the millisecond-scale temporal pattern of frequencies that are characteristic of each phoneme. Organisms also robustly learn temporal order and sequence on longer time scales of milliseconds to seconds: for example, remembering the sequence of notes in a melody, digits in a phone number, or words and lines in a poem. In some situations, organisms explicitly learn the absolute time delay between events in the world, in order to generate temporally precise expectation and responses to predictable external events. On the longest time scales, episodic memory of past events can include the relative order and recency of these events on the time scale of days, months, and years.

Research strands for this Initiative will center on how organisms learn different types of temporal information in the world, and how timing of events in the world influences learning. We will initially focus on one research strand, entitled Learning of Temporal Patterns: How do organisms recognize, learn, and remember temporal patterns of sensory stimuli, including sequences? How are these represented in the brain, and how do they guide perception and behavior? Future strands that will address other aspects of the initiative are: How does the relative timing of action, outcome, and reward influence the effectiveness of learning and duration of memory? and Cross-Modal Learning: How does timing of multi-modal sensory stimuli contribute to learning to integrate across modalities?

Each of these strands will be examined at multiple conceptual and biological levels, and at multiple time scales. Thus, most or all research networks will contribute to each strand. We expect the answer to each strand question to synthesize multiple biological, behavioral, and theoretical aspects of the issue, to achieve a novel, highly integrated view of the relevant aspect of learning.

INITIATIVE 2. TEMPORAL DYNAMICS OF THE BRAIN: What are the temporal dynamics of brain cells, brain systems, and behavior? How do these dynamics change with learning, and how do they influence learning?
(Initiative Coordinator: Andrea Chiba and Isabel Gauthier)

The temporal dynamics of the external world inevitably coalesce with the dynamics of the brain. Aligning the dynamics in the external world with the intrinsic dynamics of each brain and its behavioral output is critical to successful learning. For years, theorists have asserted that the
neural code can serve as an efficient representation of the sensory world. Whereas previous neurobiological research indicated that this representation occurred through the firing rate of neurons (rate coding), biophysical models introduce the notion of spike-time dependent plasticity (STDP), where the timing of pre and post-synaptic neuronal spikes must be within a certain number of milliseconds of each other, and the efficacy of the synapse is enhanced if the pre-synaptic spike precedes the post-synaptic spike (and depressed if the pre-synaptic spike follows the post-synaptic spike). This suggests a method by which neurons might encode relations about the world around them by using precise temporal codes. Understanding how the intrinsic time scale of STDP at synapses governs sensory perceptual learning is likely to be of fundamental relevance to understanding how the dynamics of the brain influences learning in general.

It would be computationally efficient if each spike could be identified relative to its constituent process in representing the world. The hallmark of a cell assembly or neural ensemble is that its members show a higher probability of spiking together than with members of other ensembles, even in the absence of external inputs. Such identification may be provided by a temporal phase code in which spikes of neurons within an ensemble synchronize at/or on a particular frequency or through precise timing between the spikes. It has been demonstrated that the temporal window in which spike times of one neuron were best predicted from local neural ensemble activity or EEG activity is 10-30 Hz, indicating that ensembles may be synchronized at this timescale. This time window matches the time window for forms of synaptic plasticity, thus it is hypothesized as a critical timescale for information transfer and “storage” in cortical circuits. Thus, understanding the question of how EEG frequencies or rates of modulation of EEG affect information transfer within memory systems or information storage will be important to understanding how information is represented across multiple systems in the brain.

These questions will be addressed in a research strand examining intrinsic neural dynamics: 
*What aspects of neuronal ensemble dynamics, measured by EEG, are important for learning? How is ensemble dynamics generated by interactions between neurons? How do the natural spike trains that occur during the ensemble dynamics of learning drive plasticity via STDP rules?*

The extent to which different brain systems are engaged during learning, as well as the extent to which behavioral expression is dependent on processing within a particular brain system remain critical issues in understanding the neural basis of perception, 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. Given that information is often presented in a social context, it will also be important to determine the precise time windows relevant to factors such as reinforcement and responding between individuals.

These issues will be addressed in a research strand examining the temporal dynamics of brain systems underlying behavior: 
*What are the temporal dynamics of brain systems and the interaction between different brain systems and how do they constrain learning and memory?*
The interplay between brain structures and individuals must occur in a fluid manner and on an exquisite timescale. Neuromodulation is likely to play a major role in orchestrating this exchange and setting the stage for plasticity. These questions will be addressed in a future research strand on How does neuromodulation set intrinsic dynamics for plasticity and learning?

INITIATIVE 3. TEMPORAL DYNAMICS OF MOVEMENT AND EXPLORATION: What are the temporal structures for body movements and sampling the environment and how are they learned? (Initiative Coordinators: Javier Movellan and Emo Todorov)

Nervous systems evolved to support movements at short time scales in an uncertain world. As such, biological motion can seldom rely on predetermined sequences of actions. Instead the behavior of organisms is better seen as a continuous dance with the environment, in which sensors, actuators, and internal representations are equal partners. This sensory-motor dance requires what in mathematics is known as "online control laws" (i.e. functions that specify the moment-to-moment mapping between sensory information, internal states, and the control signals sent to the organisms' actuators). Influential developmental psychologists (e.g., Piaget, Vigotsky) have long argued that these sensory-motor mappings provide the "primal soup" out of which cognitive processes develop.

A goal of this initiative is to understand how humans learn online control laws. Our interest is both the learning of specific motor sequences (i.e., open-loop control) and learning of the mappings that coordinate perception and action in real time (i.e., closed-loop control). We expect that the learning of such control laws will be different for different domains. For example, learning to walk or to ride a bicycle is likely to impose different temporal and computational constraints than learning to produce the gestures and facial expressions required in social interactions. Our goal, however, will be to find common principles across domains and to formulate a general mathematical framework for sensorimotor learning that will help explain long-standing questions in the field.

Organisms actively seek the information needed in order to perceive, act, and learn. They do so via specialized actions, aimed at gathering sensory data which reduces uncertainty, i.e., maximizes the information about task-relevant quantities thereby enhancing task performance. We will investigate the temporal structure and online control of such actions, their learning through dynamic interactions with novel and uncertain environments, and the way in which the resulting sensory data facilitates the guidance of concurrent actions. We will also develop a formal computational theory of active sensing based on the ideas of Infomax Control that are being pursued by several center members (Sejnowski, Cottrell, Bell, Todorov, Movellan). These issues will be addressed in a strand entitled; How do we actively sense the dynamically changing environment and learn to use sensory feedback to control and refine behavior?

Speech, movement, gesture, and facial expression allow us to interact with people objects and properties of an environment. The temporal dynamics of these features, their adaptive capacity, and their interplay with the environment will be considered as part of future strands addressing the following research questions: What are some of the basic temporal features of speech and language learning? and How do we learn the temporal dynamics of movements, gestures, speech,
facial expressions, and the like? Are they optimized for the environment? How well do they generalize to new dynamics environments and objects?

INITIATIVE 4. TEMPORAL DYNAMICS OF LEARNING: What mechanisms determine the time course of learning itself and what general principles explain the dynamics of learning across multiple scales and domains?
(Initiative Coordinators: Terry Sejnowski, Thomas Palmeri, and Tony Bell)

This initiative will attempt to link the networks together in order to extract various principles in the form of computational models and general theoretical insights. Indeed, a primary aim of this initiative is to allow for a formal integration of the work of all research networks. Our first strand under this initiative is: Are there general principles about the temporal dynamics of learning that can be unified into a coherent theoretical framework?

Domain-specific theories have often been proposed for different kinds of knowledge. For example, because certain visual areas in the brain respond significantly to faces, places, body parts, and other categories of objects, some theorists have argued that these reflect specialized processing modules that have evolved or developed for recognizing special categories of objects. Similarly, domain-specific theories have also been proposed for different kinds of learning. There are theories of memory, theories of skill learning, theories of object recognition, theories of categorization, and so on, and too often these theories bear little relationship to one another. As part of this strand we will pursue the formulation of general principles that link all these processes together under a unified framework. An example of a potentially unifying principle is the concept of “Infomax Control” or information maximization, which different researchers in the center have applied at different levels of analysis: from synapses (Sejnowski), to early sensory processing (Bell, Sejnowski) to oculomotor control (Cottrell, Todorov) to social interaction (Movellan).

Learning takes place not just in different domains but also at multiple time scales, from fast, one-trial learning of a new item in a familiar context, to slow learning that requires many trials, such as sensorimotor learning or expertise learning. At a neural level, mechanisms for synaptic plasticity have also been identified on multiple time scales, ranging from short-term plasticity on a millisecond time scale to long-term potentiation and structural changes that can last many hours and days. As part of this strand we will investigate whether general principles of learning exist that can be used to unify these different temporal scales. For example, the same temporal difference learning algorithm that has been used to describe reinforcement learning on a time scale of seconds within the dopaminergic system is also implemented by spike-time dependent plasticity of cortical pyramidal neurons on a millisecond time scale. Since temporal difference learning can be used to learn temporal sequences of actions to reach a goal, this suggests that cortical pyramidal neurons might be using STDP to learn temporal sequences on a faster time scale.

Future strands will examine What factors determine rates of learning and duration of memories? and How do animals or people adapt to a changing environment?
INITIATIVE 5. Development of technologies for the science of learning
(Initiative Coordinators: Scott Makeig, Javier Movellan, and Emo Todorov)

Creating a new science requires new technologies for measuring and manipulating the dynamics that the brain controls. These include such phenomena as local field potentials, whole-brain activity, muscle activations, limb and body configurations, facial expressions, and student-teacher interactions. The quality and quantity of the resulting data require unique facilities for a large-scale system for storing, synchronizing, sharing, and analyzing that data. Such technological capabilities are beyond the reach of any individual lab and can only be realized in the center mode of funding. They will enable a number of cross-cutting research collaborations which would otherwise be technologically impossible. Our plan includes the development of three such infrastructure facilities: Brain Dynamics, Motion Capture, and Data Sharing with others to be added depending upon demand.

The Brain Dynamics Facility will enable accurate measurement and analysis of whole-brain activity, by using a novel approach to combining the excellent temporal resolution of EEG and the spatial resolution of fMRI, along with the advanced data analysis and software tools developed by center participants. These capabilities will be complemented by already extant single-cell recording equipment and by the Motion Capture Facility, which together with the Brain Dynamics facility will enable simultaneous recording on brain activity and complex motor behavior. This emerging integrated technology holds great promise in terms of understanding the spatio-temporal changes in brain dynamics that underlie the process of learning. The system will be housed in UCSD's Functional Imaging Center, which includes a wide range of scanners as well as innovative methods for noise reduction. On the software side we will continue to develop and refine open-source appropriate to the new equipment including new analytic methods appropriate to the study of the temporal dynamics of learning.

The Motion Capture Facility will be developed in collaboration with the Institute for Neural Computation at UCSD. The facility will provide a range of devices for tracking behavior, including hand movements, eye movements, full body movements, facial expressions and interpersonal interactions, as well as to present stimuli that are tightly coupled with the observed behaviors (e.g. via Virtual Reality or mechanically via robotic devices). The goal is to provide researchers with the tools to manipulate time and timing and to investigate its role in learning and in the development of adaptive behavior. The facility will feature state-of-the-art equipment for marker-based motion capture, high-speed video recording, eye tracking, hand tracking, muscle recording. The facility will also be integrated with the Brain Dynamics Facility through the addition of a high-density EEG recording system for measuring brain dynamics. Complementing the hardware facilities, the Motion Capture Facility will provide a suite of software tools for data analysis and simulation, including a system for automated recognition of facial expressions, hand gestures and gaze directions; a system for probabilistic inference of joint angle trajectories, skeletal parameters and marker attachments from noisy data; and a modeling environment for simulation and visualization of musculo-skeletal dynamics.

The Data Sharing Facility will be developed in collaboration with the San Diego Supercomputing Center (SDSC) located at UCSD. Its functions will include data sharing, data analysis, and quality control. The data systems will assure that all of the shared data have,
among other components, proper IRB approval, traceable informed consent, and authorized privilege control. Sharing will be based on the concept of a datagrid - which provides data "virtualization" and makes it possible to organize distributed files into a logical collection that appears locally accessible. In addition to raw data, researchers can upload results from multiple iterations of data analysis in a variety of file formats. In this way complex data can be analyzed in collaborative fashion, while at the same time providing the access control and version control mechanisms needed to avoid data corruption. Such datagrids have become increasingly important in a growing list of scientific disciplines and the SDSC through its Storage Resource Broker (SRB) - which is becoming the software platform of choice for datagrid development – can efficiently provide these functions with only a moderate degree of tailoring being required. In addition, the facility will benefit from the new iRODS technology being developed at SDSC. The second function of the Data Sharing facility will be to provide software tools for data mining and innovative analysis of large and diverse datasets incorporating sensory stimuli, brain responses, and behavioral responses. We will utilize (and when necessary, develop) unsupervised learning methods for automated discovery of meaningful features and dimensions of the raw data. Additional funding for the development of this collaborative data analysis environment will be sought in the form of a cyberinfrastructure grant that is in the planning stages.

INITIATIVE 6. Integration of research and education
(Initiative Coordinators: Paula Tallal and Terry Sejnowski)

Our education program has several components designed for different populations:

1) K-12 students and teachers: We describe our partnership with Reach for Tomorrow and the Preuss School in Initiative 7 (Diversity). We will reach K-12 educators (teachers and administrators) through lecturing in our corporate partner Jensen Learning Corporation’s “Brain Expo” for teachers. We will volunteer our time so that scholarships for teachers (especially at our partner schools) may attend for free. We will also reach tens of thousands of K-12 educators annually through our corporate partner Scientific Learning Corporation’s website for educators www.brainconnection.com and electronic newsletter. We will contribute a quarterly column called “Advances from the NSF Science of Learning Centers” that will summarize in lay terms new scientific publications of most relevance to K-12 educators. We will also encourage responses and discussion from K-12 educators to this column as part of our “inreach” program. These outreach and inreach programs will cost us nothing but our time and will provide us with an ongoing mechanism for open and timely dialogue with K-12 educators nationally.

2) Undergraduates: First, throughout the award period, we will continue our strong commitment to directly involving undergraduates at each of our participating Universities in our research labs. Second, we will establish a Summer Undergraduate Science of Learning Institute to bring talented undergraduate students from our participating Universities to UCSD for a month of intensive exposure to our Temporal Dynamics of Learning Center research. Funding levels require that this be put on hold until year 3.

3) Graduate students and postdocs: We will establish a new “Ph.D. plus” Graduate Program in the Learning Sciences, aimed at students in Cognitive Science, Computer Science, Engineering, Psychology, and Neuroscience. A major objective of this program is to insure that students will work with center faculty to gain a balanced coverage of at least two emphasis areas in our 2 by 2
table: Experimental and computational approaches to understanding and modeling the dynamics of learning in behavior or in the brain. Our goal will be to broaden students’ training beyond their home discipline through a variety of techniques, including dinner seminars, interdisciplinary team-taught courses, lab rotations outside their home departments, and “boot camps.” Funding levels require that this be put on hold until year 3.

Also beginning in year 3, bridge postdocs will spend a year in one lab of a research network and another year in a lab at another location. This cements relations within the network and transfers techniques and knowledge from one lab to another.

4) Researchers: We will invite researchers from outside UCSD and our partner institutions to come to the Center for extended stays. We will also develop focused Summer Schools on special topics, such as computational modeling, brain imaging, slice preparations, and language learning that bring together leading researchers for two weeks of intensive lectures, labs, and discussions, and are aimed at both postdoctoral researchers and senior scientists who want to re-tool. Funding levels require that this be put on hold until year 3.

5) The public: Our premier mechanism for outreach to the public will be through The Science Network. In year 1, we will give seed money for editing equipment, record at least one Town Hall Meeting, and the lecture content at the Brain Expo for web export to teachers. These efforts will be ramped up as appropriate to the budget increments in later years.

6) Translational activities: We will begin to show translation of our science to education through further development of the “Let’s Face It!” and RUBI projects.

INITIATIVE 7. Diversity
(Initiative Coordinator: Gary Cottrell)

The investigators in the Temporal Dynamics of Learning Center are committed to the recruitment and training of individuals from underrepresented groups. A number of institutional and center strategies will be implemented to increase diversity in the center. Some of these overlap considerably with the Integration of Research and Education Initiative; in this section, we only describe additional efforts at increasing diversity. In order to monitor the success of our efforts, the PI will be responsible for supervising efforts in recruiting individuals from underrepresented groups, 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. Our administrative staff will collate data on the diversity of the center and its efforts to increase diversity.

In terms of faculty, we have identified and will continue to identify minority junior faculty from other institutions who we will ask to participate in appropriate network meetings. In terms of graduate students and postdocs, we will use the considerable diversity already existing at Rutgers Newark to attempt to recruit diverse graduate students and postdocs to our Center labs. We have two minority graduate fellowships promised to us from our Vice Chancellor of Research at UCSD that will be useful for augmenting diversity. We will also suggest scholars for the
Minority Research Seminar series at Vanderbilt as a mechanism to introduce minority faculty to our program.

Our plans for recruiting minority graduate students include the Faculty Partners Program, a mechanism intended to help us form relationships with faculty at minority serving institutions. In California, there are a large number of minority-serving institutions in the form of the state university system, and in neighboring states, there are a large number of Hispanic serving institutions. We will first concentrate our efforts on these by traveling to a selection of these institutions and giving talks in order to meet the faculty, for the purpose of inviting several faculty for a two-day visit to our Center. It is through personal relationships that faculty at these institutions will begin to encourage their students to apply to the Universities participating in our Center for graduate school.

Our plans for recruiting minority undergraduates center on two aspects of our program: 1) our partnership with the Preuss School, a 72% underrepresented minority serving charter school on the UCSD campus, and 2) the Reach for Tomorrow program, which brings inner city and other minority high school students to UCSD (and other campuses) for an intensive one to two week program.

INITIATIVE 8. Implementing, Documenting, Disseminating, and Evaluating the Network of Networks Paradigm for Scientific Inquiry
(Initiative Coordinators: Isabel Gauthier and Thomas Palmeri)

The Network of Networks is the organizational centerpiece of the center, a new collaborative research structure that aims to transform the practice of science. The success of the Perceptual Expertise Network (PEN) over the 5 years preceding the creation of our center is a proof-of-concept for research networks as powerful collaborative entities. In addition to forming other networks, we will create a new overarching structure to coordinate activities across networks engaged in a common scientific inquiry.

Implementation. The raison d’être of research networks is to provoke important theoretical questions that are not motivated or constrained by access to techniques, while making more techniques available to study these questions. Only PEN is already a fully functioning research network. Over the coming year, we will build the other three networks. Our reduced budget in years 1 and 2 means that some investigators may initially receive little or no direct funds for their research. However, as the networks provide the crucial engines for long-term scientific inquiry by the center, we will encourage and support participation of all members in network activities irrespective of their initial research funding from the center.

The power of the research network also comes from creating a long-term community of scientists eager to engage in collaborative science. Research networks must be small enough so that each investigator and their trainees can develop a solid understanding for the research of others in the group but large enough to maintain the right mix of disciplines and techniques. For instance, the PEN group has established an informal rule that network meetings must be small enough so that all the attendees can sit around one u-shaped large table – a format that fosters workshop discussions rather than conference presentations. We recognize that PEN has converged on only one out of several equally plausible models for collaborative activities:
exchanges in the TLC network-of-networks will provide opportunities to compare across different variations of this experiment in collaboration, so as to improve the efficiency of interactions in the center but also disseminate to the broader community what works well and less well as we work to meet collaborative challenges.

Network meetings will be used to build a common vocabulary and establish a shared framework for scientific inquiry. A PEN member will attend initial meetings of each network and PEN will invite members of other networks to its meetings. Later meetings, both in person and online, will be used to share progress on current collaborations, and strategically plan new frontiers for collaboration. Cross-network research strands will tie together the networks around a common set of research questions. Question-centered meetings will create synergy around a particular question that spans networks.

**Documentation.** The growth of the Network of Networks structure will be documented using the multimedia resources of The Science Network. This documentation will be used for internal assessments of the success of our model of collaborative science, and for external assessments by our advisory board, our external evaluator, and NSF. But more importantly, we will use this documentation as a key mechanism for disseminating our collaborative structure to the broader scientific community.

**Dissemination.** In addition to The Science Network, other mechanisms will allow us to broadcast our new collaborative model. One mechanism PEN has used that will be replicated in other networks is inviting some non-center members as guest participants in network and center meetings. The PEN group has already seen aspects of our collaborative model appear in collaborative efforts by colleagues.

We also plan to give conference symposia organized around topics having to do with scientific collaboration. How does scientific collaboration emerge naturally and how can collaborative research structures like ours significantly accelerate new scientific discovery? One such symposium will be submitted for the annual meeting of the Cognitive Science Society August 1-4 2007. The symposium will examine successful models (from PEN and other groups) in which a number of collaborative cognitive neuroscientists have bridged the interdisciplinary gap across disciplines and the intradisciplinary gap across methods and concepts. Additionally, noted scientists will turn an analytic lens on the value of collaborative networks or teams of researchers and will report on the logistic, social, and scientific processes that drive intellectual growth and research.

In addition to these efforts in engaging a discussion about new ways to collaborate with scientists outside the center, one of the most powerful tools to influence the science of the future resides with our students and postdoctoral fellows. Ultimately, our trainees will form a cohort of scientists ready to use, adapt, and spread a new collaborative model in their own collaborative research.

**Evaluation.** One of the first tasks for each network will be for its members to discuss and agree upon a set of principles and guidelines to represent the commitment that each member makes to the research network they are part of. While several goals will be the same across networks, each network may have its unique constraints and resources. Because networks are social organizations that exist to facilitate the challenging and complex interactions required for scientific collaborations, the commitment of each member to their network needs to be
particularly meaningful. Heads of networks will convene periodically to discuss the progress of collaborative activities and the actual level of participation from members within each network. We can learn and adapt more rapidly by learning from each other’s successes and failures.

In addition, we will more formally evaluate each network according to engagement and collaboration. Engagement combines a subjective evaluation by center members and network guests of the scientific cohesiveness, scientific utility, and collaborative involvement of the group with an objective measure of participation in meetings, online exchanges, and data sharing. Collaboration is measured by the number of publications authored by two or more network members. These data will be used to both graphically and numerically assess ongoing network activity. This will be supplemented with quantitative measures of network connectivity developed in computer science and social network theory. Networks that demonstrate insufficient growth in the first years of the center will be asked to propose specific corrective strategies. If that effort fails, the executive committee may decide to dissolve the network entirely or reconstitute it to include individuals who will embrace the collaborative model for research. Moreover, networks may be reformed, disbanded, or created to follow merging lines of scientific inquiry. We will also measure the growth of cross-network development using qualitative and quantitative measures similar to those used to evaluate within-network collaborations. Our ultimate goal is to encourage collaborative growth between and across networks. Details on these and other evaluation metrics are provided in the Evaluation section of the SIP.
SECTION III: Implementation Plan for Center Initiatives

Research Initiatives 1-4:

This section of the implementation plan reiterates our initiatives, outlines particular research strands in which the center will invest and details the projects that cohere in addressing the chosen strands. Whereas the Center initiatives and research strands provide overarching questions towards which research will be directed and knowledge built, the research networks will serve as the working and synthesizing groups, such that the efforts of the network will be dynamic. Network efforts will grow and become further defined as each network matures and diversifies the initiatives on which they are focusing. Thus, the flagship network, The Perceptual Expertise Network, often provides more detailed accounts of their efforts in each strand. This model will be followed by other networks in later stages of planning, as the center matures.

We have chosen to diversify our efforts across our four research initiatives by choosing five strands each of which directly addresses a particular initiative. This limited number of strands is necessitated by the funding limitations in the first two years of the project.

INITIATIVE 1. TEMPORAL DYNAMICS OF THE WORLD: How is temporal information about the world learned and how do the temporal dynamics of the world influence learning?
(Initiative Coordinators: Dan Feldman and Paula Tallal)

Organisms explicitly learn many aspects of the temporal dynamics of the world, from temporal sequences of basic sensory stimuli (e.g., speech sounds), to dynamics of complex events that must be recognized (e.g., gestures, or dynamic features on computer displays). Other temporal features of our world, such as the relative timing of actions and rewards, can have a significant influence on learning, even though they are not explicitly learned. Our current understanding of how temporal information is learned is quite limited. By increasing our understanding of these processes, we hope to provide insights that will improve teaching and learning of dynamic stimuli. In addition, following a successful example with speech learning, we hope to develop teaching/training tools that manipulate the temporal dynamics of the world to facilitate or improve many forms of learning.

Several specific research strands within this topic are listed below. Each represents both a key aspect of learning within this Initiative and an area of synergistic research strength within the Center. Only Strand 1.1 is prioritized for initial funding.

Strand 1.1: Learning of Temporal Patterns: How do organisms recognize, learn, and remember temporal patterns of sensory stimuli, including sequences? How are these represented in the brain, and how do they guide perception and behavior?

Research overview. Sensory stimuli often occur in specific temporal patterns composed of individual elements with consistent relative order and timing. Organisms learn to recognize behaviorally meaningful temporal patterns, and to extract information from these patterns to guide perception and behavioral responses. An example is speech, in which recurring sound
patterns are learned and recognized as basic speech sounds (phonemes), sequences of phonemes as words, sequences of words as common phrases, etc. This strand will investigate how organisms learn to recognize temporal patterns of simple sensory stimuli (visual, auditory, and tactile sequences), how this is accomplished neurobiologically in the brain, and how organisms learn to use temporal patterns to infer structure in the world, and to guide perception and decisions.

Role of each Research Network. The **Sensorimotor Network** will focus on how animals and humans learn to recognize simple temporal sequences of visual, auditory, and tactile stimuli. The primary project (1.1.1) will be a collaborative, integrated study of sequence learning in these different sensory modalities, measured on the behavioral and neurobiological levels in rodents and humans. Future planned projects will focus on how stimulus sequences are represented by dynamic patterns of brain activity. The **Interacting Memory Systems Network** will focus on how animals learn to associate discrete visual stimuli into a unified visuospatial sequence, using a novel behavioral animal model of sequence learning (Project 1.1.2). How this transformation leads to the formation of habitual or automatic behavior will also be studied. Learning will be analyzed at the behavioral and neural levels, and computational and anatomical models will be used to develop a set of predictions about the contribution of different brain structures at particular time points during learning. To date, the **Perceptual Expertise Network** has focused much of its research on understanding how people develop expertise in visually recognizing static objects. But the world is also composed of actions and events that are embedded in a temporally continuous stream of visual information. In much the same way that objects may be composed of parts yet are perceived as a single coherent object, actions and events may be composed of temporal patterns of visual cues yet are perceived as coherent actions or events. New research will examine how people learn to recognize actions represented by temporal sequences of visual events, how they develop expertise in this recognition, and whether particular kinds of learning might transfer to more abstract understanding of the physics of actions and events. The initial network project (1.1.3) in the first wave of center funding will focus on how people learn actions and events and the neurobiological basis for learning and recognition of actions and events.


The goal of this collaborative study is to understand how temporal sequences of simple sensory stimuli are learned on the behavioral and neural systems levels. Sequence learning will be studied in parallel, synchronized experiments in different sensory modalities and species (Feldman: rodent tactile sensation; Chiba: rodent visual; Harris: rodent auditory; deSa and Sereno: human cross-modal). Comparison of results across modalities and species will allow us to determine whether a common neurobiological or computational strategy underlies sequence learning and recognition in these systems. In Year 1, labs will meet to develop a common experimental paradigm. In Years 1 and 2, behavioral and neural measurements (spikes in rodents, fMRI in humans) will be performed to assess the behavioral sequence learning capacity of animals and humans, and to measure how neurons and brain networks encode sequence.
information during learning. In Years 2 and 3, results will be compared and modeled across systems to produce an integrated, cross-modality model of simple sequence learning.

Project 1.1.2. How are temporal sequences represented in the brain? What are the temporal trade-offs between brain structures during different stages of learning? Networks: IMS/SMN. PIs: Chiba/Buszaki/Harris/O’Reilly/Tallal/Bell. Project Leader: Chiba.

This project will investigate how animals learn that individual events in the environment are temporally structured into sequences, and how they gradually reduce attention and change mnemonic encoding as sequence becomes increasingly predictable. The primary initial project will be a collaborative study of how animals learn to associate a discrete set of visuospatial stimuli into a visuomotor sequence, and how the compression of these events leads to the formation of habitual or automatic behavior. In Year 1, learning will be studied behaviorally, using a novel visuospatial sequence learning task, and computational and neuroanatomical models will be developed to predict which neural structures or circuits may be essential for visuomotor sequence learning at different time points during learning. In Years 2 and beyond, brain inactivation studies and neural recording studies (simultaneous recording from multiple structures) will be undertaken to test the hypotheses set forth in Year 1. The resultant data will be analyzed with the aim of understanding the temporal brain dynamics that underlie the dynamics of sequence learning. Ultimately, these data will be used to update an existing computational model, so that the model will reflect the physiology of the system.


There is evidence for relatively independent neural processing of motion and static form. But what happens when the spatial and temporal aspects of a stimulus are integrated at a higher level? In vision, characteristic motions, gestures, and articulations convey communicative information that is only abstractly related to the highly specific representations found in primary visual areas. It is of significant interest, therefore, to better understand how the nervous system extracts the higher order invariants from such stimuli. We will extend the study of object recognition to encompass actions, or temporal sequences of visual events that represent the articulated motion associated with the behavioral actions of animate forms. At the neurophysiological level, we have already begun to explore the possibility that actions are encoded independent of actors in ventral visual areas containing both motion and object selective neural populations. At the psychophysical level, we have likewise investigated whether actions are encoded independent of individual objects or whether these objects have characteristic actions bound to them (Vuong & Tarr, 2005). Here we intend to build on these results, testing the hypothesis that action features can be learned independently of the shape features of objects. Moreover, once learned can such action features be generalized to new objects? This investigation will utilize state of the art computer graphics with parallel studies in multi-electrode recordings of single cells, fMRI studies of large-scale neural systems, and behavior.

Future Strands. The following additional strands will be considered for inclusion in subsequent plans but are not currently prioritized for funding. These strands extend the basic investigation of learning temporal patterns in the world to studying how temporal patterns are integrated across
sensory modalities and how temporal contingencies between events in the world influence the effectiveness and duration of learning and memory.

**Strand 1.2. Cross-modal learning: how does timing of multi-modal sensory stimuli contribute to learning to integrate across modalities?**

**Strand 1.3. How does the relative timing of action, outcome, and reward influence the effectiveness of learning and duration of memory?**

**INITIATIVE 2. TEMPORAL DYNAMICS OF THE BRAIN: What are the temporal dynamics of brain cells, brain systems, and behavior? How do these dynamics change with learning, and how do they influence learning?**

(Initiative Coordinators: Andrea Chiba and Isabel Gauthier)

Some important temporal dynamics are intrinsic to the way neurons and brain systems function (e.g., cellular properties of neurons, activity patterns in brain networks measured using EEG). These dynamics can influence how and what the brain learns. Other important temporal dynamics of brain systems supporting perceptual and cognitive systems have been shaped by development and experience. Understanding the temporal dynamics of perception and cognition is fundamental for understanding new perceptual and cognitive learning.

Several specific research strands within this Initiative are listed below. Each represents both a key aspect of learning within this Initiative and an area of synergistic research strength within the Center. Two strands, 2.1 and 2.2 are prioritized for initial funding.

**STRAND 2.1 What aspects of neuronal ensemble dynamics, measured by EEG, are important for learning? How is ensemble dynamics generated by interactions between neurons? How do the natural spike trains that occur during the ensemble dynamics of learning drive plasticity via STDP rules?**

*Research overview.* The hallmark of a cell assembly or neural ensemble is that its members show a higher probability of spiking together than with members of other ensembles, even in the absence of external inputs. Such identification may be provided by a temporal phase code in which spikes of neurons within an ensemble synchronize at/or on a particular frequency or through precise timing between the spikes (such a code can be measured through EEG or local field potential recordings). In addition to ensemble dynamics, further understanding of how the intrinsic time scale of spikes at synapses governs sensory perceptual learning is likely to be of fundamental relevance to understanding how the dynamics of the brain influence learning in general. The impact of individual spike trains and EEG dynamics on behavioral learning and neural plasticity will be investigated through multiple projects.

*Role of each Research Network.* The **Sensorimotor Network** will initiate studies aimed towards understanding the intrinsic timing principles of brain dynamics and the way in which they impact learning (on multiple timescales). The studies of human brain dynamics will rely heavily on the Brain Dynamics Facility, headed by Scott Makeig. In the first year, this network will be building
the foundation of the strand. In the subsequent year, they will team with the Social Interaction Network to examine intrinsic brain dynamics as they are applied to social and content specific learning. The primary goal of the **Social Interaction Network** in the first year will be to successfully establish the Motion Capture Facility. Here, a unique video-capture environment will be united with a high-density electroencephalograph (EEG) recording system, allowing simultaneous neural and motion capture. This state-of-the-art, real-time research facility will enable the Social Interaction Network (teaming with other Networks) to embark on future studies that will examine the concept 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.

**Project 2.1.1. Modulation of spike timing dependent synaptic plasticity by cortical activity waves.** Network: SMN. PIs and Project Leaders: Poo & Dan

Spontaneous and evoked activity waves have been observed in cortical slices and *in vivo*, using optical imaging, multi-electrode recording, and EEG. Using voltage-sensitive dye imaging (VSDI) and multi-patch recording of synaptic activity in isolated visual cortical slices, we found that electrically-evoked cortical waves have similar properties as spontaneous waves in these slices. Preliminary results showed that evoked waves exert a timing-dependent modulation of long-term synaptic plasticity in cortical circuits. Spike timing-dependent long-term potentiation (LTP) of excitatory synapses on layer 2/3 pyramidal cells was enhanced by waves that followed the spiking within a window of about 2 sec, but was inhibited by waves that preceded the spiking within 7 sec. These results suggest cortical waves exert a timing-dependent global impact on spike timing-dependent plasticity (STDP), affecting processing and storage of information in the cortex. We propose to further examine the regulatory effect of the wave on spike-timing-dependent long-term depression (LTD). We will also explore the relationship between the evoked cortical waves observed by VSDI and the slow waves observed by EEG, and the role of wave timing-dependent modulation of STDP on perceptual learning in awake-behaving animals and human subjects.


Neither spike timing studies in animals nor hemodynamic studies in humans can capture the rapid cortical dynamics accompanying motor learning. We will use both the brain dynamics and motion capture facilities of the Center to combine high-resolution EEG analysis, using independent component analysis to find source activities and time-frequency analysis to model cortical dynamics, with fine-grained temporal analysis of motor performance and motor learning. In one set of experiments, subjects will reach to 3-D targets under different conditions of reward feedback, while their brain activity and 3-D movements are being recorded. We will decompose the EEG activities into multiple, coordinated regional dynamics time locked to key moments in purposeful movements, and determine how these brain dynamics change as a function of movement reward and learning. Parallel experiments will study (also for the first time) the EEG dynamics accompanying walking on a treadmill, and then during natural walking with reward manipulations. By varying reward likelihood and salience, we will be in the unique position of being able to correlate changing patterns of both EEG and bodily movements in relation to changing statistical patterns of reward, a key factor in learning. During the project, we will be developing new EEG software, such as expanding our existing EEGLAB Matlab software to accept and account for parallel data types which should be useful to multiple research
communities. We will also begin to examine the relationship between brain dynamics, dopaminergic systems, and motor learning by testing Parkinson’s patients on these tasks when they are on versus off their dopamine replacement therapy.

Project 2.1.3. What are the inherent cortical EEG dynamics associated with language learning and cognitive and social development in children? (Development Project)
Networks: SMN/SIN/IMS. PIs: Benasich/Makeig/Sejnowski/Harris. Project Leader: Benasich.

This project investigates how developmental changes in brain temporal dynamics, as measured by resting EEG and ERPs, impact learning. Specifically, are the changes in neuronal synchrony that occurs during cognitive processing, in particular fast gamma-frequency oscillations, linked to emerging language and cognition? Such high-frequency cortical activity has been linked to a wide variety of higher cognitive processes including attention, perception and memory. We will examine the maturation of EEG power spectra in children from 16 through 36 months of age, using dense array EEG/ERP collected during spontaneous (resting) EEG epochs. We have demonstrated that individual differences in the distribution of power spectra in the 30 to 50 Hz (gamma) range in frontal cortex are strongly associated with developing language and cognitive skills. Gamma power was also reduced relative to controls in a sample of children at higher risk of language disorder as a function of family history. These cognitive abilities show dramatic development at around 16 to 24 months that is hypothesized to correlate with a steep increase in the density in brain cells in relevant brain areas. Our work to date suggests that the development of cognitive abilities may occur simultaneously with the brain development necessary for these high frequency oscillations. This project involves development of state-of-the-art electrocortical analysis techniques, including single trial analyses of coherence and power spectra within resting EEG, that will allow exploration of not just group averaged data, but also the finer temporal dynamics of representation and discrimination in an individual child.

Project 2.1.4 Are there EEG markers relevant to elicitation and timing of facial expression during math tutoring sessions? (Development Project)

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 EEG and the motion capture of gesture dynamics, we will employ automated facial expression measurement tools already developed in the Machine Perception Laboratory 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. Moreover, in collaboration with Judy Reilly, we will undertake analysis of verbal as well as nonverbal behavior including language content, facial expression, and gesture, and the temporal relations between them. The data will be used to develop statistical dynamical models that capture the timing of the head movements, eye movements, and hand/arm movements and facial expressions of students and teachers, as they relate to dynamics intrinsic to the brain.

STRAND 2.2 What are the temporal dynamics of brain systems and the interaction between different brain systems and how do they constrain learning and memory?
Research overview. Learning and memory require the interplay of different systems across the brain involved in perception and categorization of incoming information, maintenance of current goals and intentions, active manipulation of stored information and decisions that lead us to act on the world. The acquisition of skills and knowledge depends on these systems working together efficiently, in a temporally coordinated manner. Over the course of learning, systems that were once crucial may be bypassed and new systems may come to play an important role. To fully describe the mechanisms of learning and memory, it is not sufficient to understand local dynamics at the level of neurons or neuronal ensembles; we must also account for the finely tuned temporal dynamics of interactions between brain systems. This level of analysis can also help unravel the functional locus of changes occurring over learning: many behavioral phenomena can be modeled by changes at a variety of processing stages, from perception to memory to decisions, and temporal dynamics can help constrain models and reject invalid neural architectures.

Role of each Research Network. The way in which information is organized in the brain changes with time and experience. The Interacting Memory Systems Network will pursue studies aimed towards understanding how a particular event in time is made distinct from another. Focus will be given to the role of the hippocampus in processing recent versus remote events and the interplay between brain structures across duration of knowledge. Network efforts will then examine the parameters of learning that result in enduring knowledge. Consideration will be given to the computational and neural parameters that underlie these aspects of learning and memory. The primary goal in the first year will be to establish individual projects, sharing information and techniques in considering the timing functions of hippocampal/cortical systems in subserving learning and in organizing information for future retrieval. In subsequent years, projects will be expanded and added to address specific hypotheses that arise from year one, integrating real-world learning with neural systems analyses and models. The Sensorimotor Network will begin to examine developmental neural correlates of perceptual abilities (specifically auditory) that relate to and predict the ability to learn in other domains. The focus on prediction makes this effort a longitudinal effort. The Sensorimotor Network will team with the Interacting Memory Systems Network to begin to develop animal models for parallel studies. They will also work towards sharing analytical techniques with other networks. The Perceptual Expertise Network will focus their efforts on the way in which experience shapes the moment-to-moment dynamics involved in perceptual decisions. Experts recognize objects more quickly and at more specific levels of abstraction than novices. Their perception of objects is more holistic than novices and they more efficiently extract discriminating information. Unraveling the temporal dynamics of perceptual decisions will allow an explanation of how the initial perception of the expert differs from that of the novice, why certain kinds of perceptual experiences but not others result in expertise, how transitory changes in neural states are related to specific changes in behavior, and why certain kinds of brain damage or cognitive impairments might lead to breakdowns in perceptual expertise. The first PEN project examines the time-course of object processing in novices and experts using a combination of behavioral studies, computational modeling, and ERPs. The second project focuses on a specific temporal marker observed in ERP components (the error-related negativity, or ERN) and how it systematically changes over the time-course of learning.

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. Complex systems analyses will be applied and subsequent predictions will be made regarding the functional role of new neurons in the hippocampal system. The focus for the first year will be on the role of adult hippocampal neurogenesis in learning. The primary goal in the first year will be a collaborative effort (Wiles and Gage) in which they assess the computational implications of gradual integration of new neurons into the dentate gyrus of the hippocampus. In subsequent years, a larger collaboration across multiple laboratories will pursue opportunities to explore the predictions of the computational model behaviorally and physiologically. In addition consideration will be given to the possible role of neurogenesis as a "time constant of learning" (on the order of weeks) when viewing experimental data from other projects in the group.


Our ability to recall a spatio-temporal sequence of events from our personal past experience is called episodic memory. Because these episodic memories are believed to be responsible for the creation of the ‘self’, many investigators believe that such ‘mental travel back in time’ is uniquely human. Ample clinical evidence shows that the hippocampus and associated structures are critical for coding and retrieving one’s past episodes. A critical test for episodic memory in experimental settings is ‘free recall’. The hypothetical neuronal substrate for such mechanism is a network whose member assembles can advance each other in time. Neurons associated with a particular recalled item should activate other neuronal assemblies that represent events in the same spatial and temporal framework.

Experiments with rodents have revealed that cell assemblies in the hippocampus respond differentially to spatial cues. For example, subsequently visited places and their distances are represented by the temporal relationship among the neurons, analogous to the encoding mechanism of sequential items in an episode. However, because environmental cues are believed to continuously control hippocampal neurons, and testing recall sequences in animals without external stimuli is difficult, no previous studies have examined the neuronal mechanisms of free recall or its evolutionary predecessor in animals. Here we propose to examine whether and how hippocampal cell assemblies evolve internally when environmental cues are fixed and information from the body is kept constant while the rat is running in a wheel (‘frozen’ in space). On the basis of preliminary observations demonstrating that cell assembly sequences in the hippocampus evolve perpetually even where rats are ‘frozen’ in space (i.e., running in a wheel), we expect to show that cell assembly sequences are perpetually activated by the internal dynamics of hippocampal networks. Specifically, we will test (a) whether the different environmental contexts will give rise to unique evolving population sequences while the rat runs.
in the same wheel, (b) clarify the conditions that initiate those sequences, (c) examine how cell assembly sequences are affected by transient (2 sec) inactivation of all neurons in the hippocampus and (d), whether we can predict the future choice of the rat in the delayed spatial alternation task from the perpetually shifting sequence episodes during wheel running (i.e. the delay time). These physiological findings will provide a link to understanding the mechanisms of episodic free recall. They may also provide an alternative coding mechanism of working memory, different from persistent activity of a circumscribed cell assembly.


As time passes after learning, and recent memory becomes remote memory, a number of changes occur in the neural organization of memory. Most notably, the hippocampus becomes less important and some cortical areas appear to take on a larger role. We propose to carry out prospective studies of recent and remote memory using fMRI in humans and reversible lesions in the rodent to examine how the function of the hippocampus and the neocortex might change over time, as recent memories become remote memories. For the fMRI studies, volunteers will study 320 scenes and then take recognition memory tests later that same day as well as 1 day, 2 weeks, and 1 month later (80 scenes tested at each interval). All recognition tests will be taken during scanning. Thus, we will be able to determine if brain activity changes as the memories become more remote. Our design and data analysis will reduce the influence of nonspecific factors that could operate across the retention interval. The work with rodents will be complimentary to the work with humans. Rats will be trained using the novel object recognition task, a task that we have studied in some detail and that yields long-lasting memory. Reversible lesions of the hippocampus (or specific cortical areas identified as important from the fMRI studies above) will be made with osmotic minipumps for 1 week immediately after learning, or for 1 week beginning 4 weeks after learning. Following inactivation, memory will be assessed. These studies should shed light on fundamental questions about the temporal organization of memory.

Project 2.2.4 *How does stimulus spacing predict performance at longer time scales? What neural/computational processes are engaged at different time scales?* Network: IMS. PIs: Pashler/Mozer. Project Leader: Pashler.

Pashler and Mozer will collaborate to understand mechanisms of human learning and memory. In particular, they will focus on the relationship between the spacing of practice sessions and the subsequent retention of material. This relationship has a strong dependence on the time scale: Data currently being analyzed are revealing a complex interaction between the duration of retention and the optimal spacing of practice. If material is to be retained for only seconds, then short spacing of study is superior to longer spacing. A very different profile of optimal spacing of material is observed if the material is to be retained for months or years—the goal in most real educational contexts. The proposed research will allow for the collection of additional data to shed light on these effects, and also for a neurocomputational analysis of the causes of spacing phenomena. Existing models and their shortcomings will be analyzed, and models consistent with neuroscientific data will be proposed and explored.

Project 2.2.5 *Can we determine how efficient processing of specific temporo-spectral aspects of the auditory stream is related both concurrently and predictively to processing efficiency in the*

This project studies the intrinsic temporal dynamics of the brain processes that are necessary for normal cognitive and language development. We will examine dense-array EEG/ERP ‘markers’ that accompany linguistic and cognitive abilities across development in infants (3-6 months through 5 years of age), assessed using a large battery of behavioral tests. The goal is to determine how efficient processing of the specific temporal-spatial aspects of the auditory stream are related both concurrently and predictively to processing efficiency in three domains: non-linguistic, language and cognitive. For example, what parameters make a difference in how efficiently and how well the child learns language (both expressive and receptive)? How do attention, short-term memory, demographic variables and general cognitive abilities contribute to this process? We will generate developmental trajectories for both specific temporal as well as global parameters and examine their impact on children’s “learning curves”. Canonical Correlation Analysis (CCA) will be used to evaluate and model the relations between our extensive behavioral data set and the EEG/ERP. With this method, one can effectively explore two or more data sets and determine whether linear or non-linear relationships exist between data sets. These techniques provide the ability to make sense of the large amounts of information obtained from dense array ERP techniques and thus can provide a bridge between neural systems and behavior across development.


The goal of this project is to map the time course of perception and decision that occur whenever we perform judgments about visual objects, for different goals such as detection, basic-level categorization, or subordinate-level identification. In particular, we will ask how the time course of perceptual encoding, we will manipulate stimulus presentation duration in a backward masking paradigm. To map the time course of post-encoding decision mechanisms, we will keep presentation duration constant and vary the time allotted to make a response. Different task manipulations, such as inversion, spatial frequency filtering or image degradation, will be used to test hypotheses about the putative sequences of stages that may be involved in object processing. We will also examine ERP components within the time-course of a single trials and how they change over the time-course of learning. One working hypothesis is that different decisions, such as object detection and categorization, may be based on the same general mechanisms involved in perceptual decision making, but the difficulty of those perceptual decisions can be selectively manipulated. This hypothesis differs from recent claims that detection and categorization cannot be dissociated in time.


In a reinforcement learning task, two types of errors are associated with distinct ERPs. A "feedback" error-related negativity (ERN) is elicited when participants receive negative feedback regarding the inaccuracy of a previous response. A "response" ERN is elicited when a participant
commits an error despite full knowledge of the correct response. In the case of the feedback ERN, the participant is unaware of the error response until corrective information is provided whereas in the case of the response ERN, the participant realizes the error at the time of response. A simple category learning task will be used to examine the shift from a feedback ERN to a response ERN over the time-course of learning. Participants will be asked to classify simple objects into one of three stimulus categories. It is hypothesized that during the early stages of learning, errors will generate feedback ERNs as participants acquire information about the diagnostic features of the target categories. Once the diagnostic features of the category have been learned, response ERNs will occur and will be further induced by having participants classify stimuli under increased time constraints. The kind of errors that participants commit during expert training provides a neurophysiological index of their level of expertise. At the beginning of training, participants as novices will produce feedback ERNs and later on, as they acquire expertise, their errors will elicit response ERNs. The value of this approach is that the temporal dynamics of expertise are revealed via changes in brain activity. Differential ERN markers could potentially be useful to systematically control online learning by discriminating different kinds of errors electrophysiologically.

Future Strands: Interplay between brain structures must occur in a fluid manner and on an exquisite timescale. Neuromodulation is likely to play a major role in orchestrating this exchange and setting the stage for plasticity. Thus, a future strand for consideration focuses on the role of neuromodulation:

Strand 2.3. How does neuromodulation set intrinsic dynamics for plasticity and learning?

INITIATIVE 3. TEMPORAL DYNAMICS OF MOVEMENT AND EXPLORATION:
What are the temporal structures for body movements and sampling the environment and how are they learned?
(Initiative Coordinators: Javier Movellan and Emo Todorov)

This initiative seeks to understand how humans learn real-time sensory-motor control laws. Our interest is both the learning of specific motor sequences and the learning of mappings that coordinate perception and action in real time. Are there common principles across domains and can we formulate general mathematical frameworks for sensory motor learning that will help explain long-standing questions in the field?

Several specific research strands within this topic are listed below. Each represents both a key aspect of learning within this Initiative and an area of synergistic research strength within the Center. Only Strand 3.1 is prioritized for initial funding.

STRAND 3.1. How do we actively sense the dynamically changing environment and learn to use sensory feedback to control and refine behavior?

Research overview. Organisms actively seek the information needed in order to perceive, act, and learn. They do so via specialized actions, aimed at gathering sensory data which reduces uncertainty about task-relevant quantities and thereby enhances task achievement. Here we will
investigate the temporal structure and online control of such actions, their learning through dynamic interactions with novel and uncertain environments, and the way in which the resulting sensory data facilitates the guidance of concurrent actions. We will also develop a formal computational theory of active sensing.

Role of each Research Network. The Perceptual Expertise Network will focus on how external sensors are driven towards efficiently collecting appropriate information for rapid visual recognition and how strategies change with perceptual expertise. The first stage of PEN’s efforts in this strand will include experimentation and computational modeling (Project 3.1.1). The second stage of PEN’s efforts will involve teaming with members of the Sensorimotor Network and the Social Interaction Network, working towards the development of a computational theory of active sensing. The Sensorimotor Network will focus their efforts on building a foundation for studying active sensing. In year one, they will focus on how sensory systems use their sensors to gather information, how stimulus timing affects perception, and they will begin considering whether there is a general theory of active sensing. In the second stage of work, further attention will be given to how discrete sensory sampling provides continuous perception, alongside a collaborative effort to investigate the dynamics between sensors and a changing environment. The primary efforts of the Social Interaction Network will be toward establishing the Motion Capture Facility in preparation for pursuing Project 3.1.4 in year 2. During this phase, there will be substantial participation in the collaborative effort to develop a general theory of active sensing.

Project 3.1.1 How do eye movements influence recognition and how do they change with perceptual expertise? Network: PEN. PIs: Cottrell/Palmeri. Project Leader: Cottrell.

We will investigate how the sequence of an observer’s eye fixations depends on the image properties, the task requirements and the subject’s expertise. We will study recognition of both familiar stimuli such as faces and novel, unfamiliar objects, in order to better control and understand the role of experience. Our hypothesis, based on preliminary results, is that the learning of eye-movement routines goes through three stages: (1) a relatively task-independent stage that passes quickly as subjects become familiar with the task and the stimuli, (2) a task-driven stage where subjects focus on locations that are most relevant to the task, (3) an information-efficient stage where locations are selected based not only on task relevance but also on expected information gain. This would explain the sequential behavior of information sampling based upon obtaining the most useful information first; but what is useful changes with expertise, as neural receptive fields adapt to represent the discriminating information.

Project 3.1.2 How do we learn to maintain a smooth, continuous perception of the temporal dynamics of the world, despite discrete visual sampling by eye movements? Network: SMN. PI and Project Leader: de Sa.

How do we learn to experience the visual world seamlessly despite the constant discrete nature of our saccadic sampling? In 2005, Morrone and colleagues reported an intriguing finding: the perceived order of stimulus flashes is reversed when the flashes occur within a window immediately prior to a saccade (Morrone et al, 2005, Nat. Neuro.). They also reported that the observer’s perception of the interval between the flashes was increasingly distorted for mean stimulus onset times close to this critical window. We have determined that the perception of auditory stimuli prior to an eye movement is not distorted in this way and will now use paired
auditory and visual stimuli to study the perception of each individual flash relative to the time before the eye movement (using the auditory stimulus as an undistorted marker). We will then use EEG recording and ICA (Independent Component Analysis) processing to look at the event related potentials caused by the flashes and clicks and examine their distortion prior to eye movements. We will discuss the issue of discrete sampling with other members of the Center to explore the generality of our findings. Finally we will create models to try to understand this surprising phenomenon in the context of the requirements and limitations of discrete sensory sampling. Our hypothesis is that the temporal distortion of visual processing prior to an eye movement is an adaptation (either learned or developed through evolution) to allow for continuous action that is dependent on discrete visual input. We are using the NSF IGERT eye tracker for this work.

Project 3.1.3. What is an appropriate computational theory of active sensing?

We will develop and test a computational theory of active sensing in the broader context of sensorimotor integration. Task achievement will be modeled from the viewpoint of stochastic optimal control – where one defines a performance criterion and seeks the feedback controller maximizing expected performance. Sensory processing will be modeled from the viewpoint of Bayesian inference – where one integrates all sources of information and computes a statistically-optimal estimate used to drive the feedback controller. The acquisition of sensorimotor control laws through experience will be modeled from the viewpoint of Reinforcement Learning. To capture active sensing in this general framework, we will model actions that affect the flow and quality of sensory data.

Project 3.1.4 What are the exploration strategies involved in dynamic interactions with the environment, and how are they learned and coordinated with concurrent exploitation strategies? (Development Project) Networks: SIN/SMN. PIs: Movellan/Todorov. Project Leader: Movellan.

We will investigate active sensing in the context of dynamic interactions, and will develop computer animations which respond in real time to facial expressions and hand gestures. Their response will be governed by well-defined but unknown to the subject rules – which will have to be learned (either explicitly or implicitly) in order to manipulate the animated object successfully. Such experiments will allow us to study the tradeoff between exploration and exploitation: at each point in time the subject can either pursue the task directly, relying on information already available, or try new facial expressions and hand gestures so as to probe the animated object and gather additional information.

Project 3.1.5 How might temporal perception of motor sequences in speech relate to language learning? (Development Project) Networks: IMS/SMN. PIs: Elman/Mozer/ Tallal/Poizner. Project Leaders: Elman & Mozer.

Rather than studying language understanding in the abstract, we'll create a microworld and interpret language in terms of visualization of actions in the microworld. This will involve modeling language understanding via statistical techniques that incorporate syntactic, semantic, and pragmatic information simultaneously. Language intrinsically involves a temporal unfolding, on the time scale of seconds wherein the interpretation process involves simultaneous, interacting constraints. We will consider how neural representations are organized to serve this process.
**Future Strands.** Speech, movement, gesture, and facial expression allow us to interact with people, objects, and properties of an environment. The temporal dynamics of these features, their adaptive capacity, and their interplay with the environment will be considered as part of future potential research strands.

**STRAND 3.2.** What are some of the basic temporal features of speech and language learning?

**STRAND 3.3.** How do we learn the temporal dynamics of movements, gestures, speech, facial expressions, and the like? Are they optimized for the environment? How well do they generalize to new dynamics environments and objects?

**INITIATIVE 4. TEMPORAL DYNAMICS OF LEARNING:** What mechanisms determine the time course of learning itself and what general principles explain the dynamics of learning across multiple scales and domains?  
(Initiative Coordinators: Terry Sejnowski, Thomas Palmeri, and Tony Bell)

Learning takes place on multiple time scales, at multiple levels, in a variety of domains, relying upon a diversity of brain systems. Are there general principles about the temporal dynamics of learning across scales, levels, domains, and systems that can be unified into a coherent theoretical framework?

Several specific research strands within this topic are listed below. Each represents both a key aspect of learning within this Initiative and an area of synergistic research strength within the Center. Only Strand 4.1 is prioritized for initial funding.

**STRAND 4.1.** Are there general principles about the temporal dynamics of learning that can be unified into a coherent theoretical framework?

*Research overview.* The goal of this strand is to synthesize research activities both within research networks and across the network of networks into a coherent theoretical framework to elucidate the role of time and timing on learning. Of particular interest is to develop a better understanding of how learning operates across different domains, time scales, and levels of analysis. Activities include: (1) Formulation of mathematical and computational theories of learning and adaptive behavior that include time and timing as an essential component. (2) Modeling empirical data that helps establish links between different research efforts. (3) Research and reviews that elucidate the temporal dynamics of learning across different domains. (4) Empirical studies whose goal is to discover general principles of learning across different domains.

*Role of each Network.* Integrating across timescales, levels, and domains is perhaps the largest challenge facing all of the Networks in the Center. The **Sensorimotor Network** will begin a primary and longstanding theoretical effort aimed towards exploring solutions to this challenge. In phase 2 of this Strand, the Sensorimotor Network will team with the **Interacting Memory**
**Systems Network** to plan experiments and theoretical efforts aimed towards understanding how the brain builds regularities that underlie prediction. The **Perceptual Expertise Network** will initially focus efforts on empirical studies that can help uncover general principles of how highly-learned categories – categories of expertise – are processed in time. This work will place the processing of categories of expertise in competition in order to reveal the fine details of temporal processing, and to place constraints on theoretical models of perceptual expertise. The **Social Interaction Network** will focus on developing theoretical models that account for the way in which a system detects some of the non-verbal behaviors involved in social interactions.

**Project 4.1.1. Can general principles account for specialization in the visual system for different domains of expertise (e.g., faces, letters, musical notation, cars, novel objects, etc.)?** Network: PEN. PIs: Entire Network Effort. Project Leader: Gauthier.

PEN will work as a group to compare the temporal interaction of different types of perceptual expertise, e.g., expertise required to identify letters, read musical notation, recognize objects from touch, identify birds from songs, etc. One specific experimental approach we have used is to study competition between two or more domains. Most people possess visual expertise in domains like face perception and letter recognition, and many people also possess expertise in areas related to their work or hobbies. To the extent that multiple types of expertise rely on common resources, they will interfere with one another. This competition often reveals itself in the time-course of decision, as revealed by behavior or ERP components. This competition can arise at different stages during the time-course of a judgment about an object within a domain of expertise, from perception to categorization to response. Contrary to the view that expertise should lead to encapsulated skills that do not interfere with one another, we instead find evidence for competition. However, timing is crucial: while we may not be able to perceive objects of expertise in two domains simultaneously without interference, this competition is resolved at longer time intervals. The specific temporal dynamics of this competition will be explored and used to constrain models of expert perception and recognition. An important and long-term goal will be to develop dynamic models of expertise that take time seriously and which can account for both the relatively slow changes occurring with learning as well as the rapid temporal dynamics of competition.


It is widely accepted that social structures are made from networks of organisms which are made from networks of neurons, themselves composed of networks of protein complexes which are in turn composed of networks of macromolecules, and so on. An implication is that learning and dynamics at the social, sensory-motor and synaptic levels must be related to each other through the equations that transform the state variables at lower levels to those at higher levels. The learning equations at a higher level (e.g., STDP) then appear as state equations at a lower level (macromolecular). The distinction between state dynamics and learning dynamics is erased. The goal of this project is to unify these observations with the Bayesian theory of probabilistic learning and inference. Likelihoods and posteriors are properly seen as conditional probabilities across levels. Multi-level state vectors will be defined along with their temporal dynamics, which consists of upward emergences and downward constraints. Although the project is ambitious, multi-level learning will be demonstrated on simple model systems such as networks of spins, and more realistic models such as an inter-level model of STDP.
Collaboration with Javier Movellan and Emo Todorov will ensure that the theory properly embeds current probabilistic learning theory as applied to sensory-motor phenomena. Discussion with Dan Feldman will augment the connection between sensory-motor learning and spike-timing based representations and learning.

*Project 4.3.3. How do expectations of appropriate timing of social interactions influence detection of social cues relevant to learning? (Project Under Development)* Network: SIN. PIs: Bartlett/Deak/Movellan. Project Leader: Movellan.

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 increasing physical contact. Research shows that this matching of behavior has a subconscious affect on individuals, making them feel more relaxed, more open, and feel more favorably disposed to the interaction. There is some suggestion that such behaviors also increase information transfer between individuals. A major focus of the Social Interaction Network is automated recognition of nonverbal behavior such as expression, head movement, and eye gaze. Theoretical models for detection of these behaviors will be put forth.

*Project 4.1.4: How does the brain build regularities that underlie prediction? (Project Under Development)* Networks: IMS/SMN. PIs: Chiba/Bell/Tallal/Sejnowski. Project Leaders: Chiba and Bell.

The goal of this project is to investigate the behavioral dynamics of organisms learning to predict the world, while attempting to identify the relevant time scales for different learning processes, and to determine whether those time scales can shift as temporal statistics are altered in the world. The vehicle for attempting to accomplish this goal will be designing experiments that can be produced and analyzed with the formalism of optimal prediction and control theory. The “world” can essentially be set by Bayesian models such that time constants and stimulus predictions are built into “worlds” with “slow”, “medium” and “fast” time constraints (Bayesian operant worlds of a sort). In the case of rats, monkeys, and humans, the model can test for the optimal durations between stimuli that facilitate learning rate and/or inference. In social robots and in humans the model(s) can be used to set the pace of social interactions in a concordant manner. Each experimental result will address the effect of systematically changing the time constant of the experimental world. Whereas the temporal world is systematically changed across all experiments, the embedded prediction problem varies by experimental domain. This provides a venue for the abstraction of general principles of learning relevant to time.

**Future Strands.** Of primary importance to learning theory are the factors that determine how learning and memory will proceed at future time points. Of primary importance to the success of a person or organism in any learning environment is their ability to adapt to the changing demands of the environment. This is a feature for which there are large individual differences. Future strands focused on these foundational issues will be considered for inclusion.

**STRAND 4.2. What factors determine rates of learning and duration of memories?**

**STRAND 4.3. How do animals or people adapt to a changing environment?**
RESEARCH TIMELINES:

Year One:
All full projects will be initiated in year one and expected to extend through year two. Many of the projects have the potential to be multi-stage projects and may be expanded well beyond the second year (pending results and funding). Each of the projects will receive 30K seed money that will be distributed to the project leaders. The project leaders will be responsible for ensuring the successful planning and initiation of the first stage of the project. Each of the Development Project teams will be eligible to request meeting money for the purpose of getting together to further develop their project and share information.

Year Two:
Each of the Development Projects (noted by Development Project) is eligible for funding in Year 2. Year One projects will also be continued in Year 2 (providing that they demonstrate that they have met Year 1 Milestones). Additional projects will be added in Year 2, in order to further address the Research Initiatives.

In year 2 of the grant, after preliminary work has been done within each network there will also be the addition of “Modeler’s Meetings,” and “Timescale Meetings”, in order to begin integrating across and within the operating scales of the science.

Further work will be possible after the Data Sharing Facility is up and running in year 2. Modelers should be able to extract data from the facility (alongside a detailed account of the experimental conditions under which it was collected) in order to use it to test and modify their models. Machine learning researchers associated with the grant will begin to be able to mine data in year 3 at least, if not earlier. This work is complementary to the modeling work, as it has a goal of finding regularities in the data, without a preconceived notion of what those regularities may entail.

First Year Project Milestones: At the end of year one, every funded project should meet the following milestones:
1. Personnel with appropriate expertise for project are in place.
2. The project has been initiated.
3. Initial data have been successfully collected, demonstrating project feasibility.

Resource Allocations for Research:
(Note: All dollar amounts refer to direct costs. Total costs are detailed in the accompanying budget.)
30K (research money after indirect costs) will be allocated to each of the listed projects. A small amount of funding has been set aside for specific requests from project teams (e.g. equipment, travel funds, etc.). Development projects will not receive funding. Instead, members of development projects are eligible to request travel funds for project development meetings. 90K will be invested to begin work on Initiative 1 (Strand 1). 270K will be invested to begin work on Initiative 2 (Strands 1 and 2). 90K will be invested to begin work on Initiative 3. 30K will be invested to begin work on Initiative 4. The PEN Network is also working on Initiative 4, but has agreed to use existing funding in year 1 with the addition of potential meeting money. The
funding allocations represent the group’s priorities for each of the strands in Year 1. A small allocation will be given to Initiative 4, in order to initiate a very challenging long-term strand that has potential to integrate all of the work in the Center.

INITIATIVES 5-8:

This portion of the implementation plan reiterates our goals for initiatives 5-8 and makes explicit how and when they will be accomplished.

INITIATIVE 5. Development of technologies for the science of learning
(Initiative Coordinators: Scott Makeig, Javier Movellan, and Emo Todorov)

Creating a new science requires new technologies for measuring and manipulating the dynamics that the brain controls. These include such phenomena as local field potentials, whole-brain activity, muscle activations, limb and body configurations, facial expressions, and student-teacher interactions. The quality and quantity of the resulting data require unique facilities for a large-scale system for storing, synchronizing, sharing, and analyzing that data. Such technological capabilities are beyond the reach of any individual lab and can only be realized in the center mode of funding. They will enable a number of cross-cutting research collaborations which would otherwise be technologically impossible.

Scott Makeig will direct the start-up of the Brain Dynamics Facility, with the assistance of Tzyy-Ping Jung. Given the limited funds, the first stage of creating a brain dynamics facility will include integrating a high-density EEG system as part of the Motion Capture facility. This issue is not trivial, as several technical limitations regarding preserving signals and preventing the intrusion of noise from other components in the facility will have to be overcome. Once completed this would represent the first facility combining these technologies.

Javier Movellan, Emo Todorov, and Howard Poizner will start-up the Motion Capture Facility. The Center is investing the majority of its resources in this facility. Yet, there will be enormous added value to this facility due to the establishment of an industrial partnership (currently under formation), in which a 50% price reduction will be granted in exchange for analysis routines from Movellan and Todorov.

The Data Sharing Facility will be developed in collaboration with the San Diego Supercomputing Center (SDSC) located at UCSD. Its functions will include data sharing, data analysis, and quality control. Dr. Mark Appelbaum will supervise a programmer who will set-up the administrative and organizational portion of the Data-Sharing Facility. Thereafter, Richard Marciano and Reagan Moore will supervise a programmer who will begin building the GRID portion of the Data-Sharing Facility. Additional funding for the development of this collaborative data sharing and analysis environment (as originally envisioned) will be sought in the form of a cyberinfrastructure grant that is in the planning stages.

Timeline and Milestones:
Year One:
By the end of year one, the Motion Capture Facility will be functional (assuming the timely shipment of equipment). Integration of an EEG system from the Brain Dynamics Facility will have been tested, but may not be functional due to the technical obstacles described above. By the end of year one, the administrative portion of the Data-Sharing Facility will be developed and the GRID portion of the facility will be in the development phase.

**Year Two:**
By the end of year two, the Data-Sharing facility will be functional and several users from each network will have data stored on the GRID.

Due to finances, the enhanced Data-GRID and the Brain Dynamics Facility will have to be initiated in year three (after further funds become available).

**Resource Allocations:**
One month of salary for Jung, Movellan, Todorov, and Poizner have been allocated, in order to allow a percentage of their time to be invested in the start-up of the Motion Capture Facility. Four months of programmer time (at 50% time) for the administrative database and seven months of programmer time (at 50% time) has been allocated for the development of the Data Sharing facility. All equipment resources have been allocated for the shared Motion Capture and Brain Dynamics Facility. Existing equipment at SDSC will be utilized for developing the Data Sharing Facility.

**INITIATIVE 6. Integration of research and education**
(Initiative Coordinators: Paula Tallal and Terry Sejnowski)

In order to facilitate initiation of our research and education initiatives, while maintaining the bulk of our resources for science, the following implementation measures will be taken.

1) **K-12 students and teachers:** We describe our partnership with Reach for Tomorrow and the Preuss School in Initiative 7 (Diversity). We will reach K-12 educators (teachers and administrators) through lecturing in our corporate partner Jensen Learning Corporation’s “Brain Expo” for teachers. We will volunteer our time so that scholarships for teachers (especially at our partner schools) may attend for free. We will also reach tens of thousands of K-12 educators annually through our corporate partner Scientific Learning Corporation’s website for educators [www.brainconnection.com](http://www.brainconnection.com) and electronic newsletter. We will contribute a quarterly column called “Advances from the NSF Science of Learning Centers” that will summarize in lay terms new scientific publications of most relevance to K-12 educators. We will also encourage responses and discussion from K-12 educators to this column as part of our “inreach” program. These outreach and inreach programs will not cost us anything but our time and will provide us with an ongoing mechanism for open and timely dialogue with K-12 educators nationally.

Through the UC COSMOS Summer Program, a workshop will be given to high school students on the temporal dynamics of learning. We intend to do one round of this each year, as it does not cost us anything but our time. Additionally, UCSD’s existing Neuroscience Outreach Team will
develop and incorporate a unit on temporal dynamics of the brain for in their outreach to K-12 students and teachers.

The Center Program Representative (Andrew Kovacevic) will facilitate these partnerships and arrange plans to ensure that the programs run smoothly. Center investigators will be responsible for entering all reporting data into the Center administrative database, in order to record and document these activities.

2) Undergraduates: First, throughout the award period, we will continue our strong commitment to directly involving undergraduates at each of our participating Universities in our research labs. Each laboratory will report their undergraduate research trainees and the projects on which they worked. Center investigators will be responsible for ensuring that this information is entered into the Center administrative database. Through the UCSD Educational Advancement Office, Michael Dabney will coordinate matching efforts between Center investigators and incoming students participating in academic enrichment programs. The Summer Undergraduate Science of Learning Institute will be put on hold until year 3.

3) Graduate students and postdocs: Starting in year 3 of the project, we will establish a new “Ph.D. plus” Graduate Program in the Learning Sciences, aimed at students in Cognitive Science, Computer Science, Engineering, Psychology, and Neuroscience. A major objective of this program is to insure that students will work with center faculty to gain a balanced coverage of at least two emphasis areas in our 2 by 2 table: Experimental and computational approaches to understanding and modeling the dynamics of learning in behavior or in the brain. This program will be initiated in year 3, pending the availability of funds.

Starting in year 3 of the project, bridge postdocs will spend a year in one lab of a research network and another year in a lab at another location. This cements relations within the network and transfers techniques and knowledge from one lab to another. The Center Program Representative (Andrew Kovacevic) will be responsible for assisting with travel and housing arrangements to ensure that this is possible.

4) Researchers: In year one, we will invite researchers from outside UCSD and our partner institutions to come to the Center to give talks. Planning will be facilitated by Program Representative, Andrew Kovacevic.

5) The public: Our premier mechanism for outreach to the public will be through The Science Network (TSN). In year 1, we will provide seed money for editing equipment, record our all-hands meeting and the lecture content at the Brain Expo for web export to teachers. These efforts will be ramped up as appropriate to the budget increments in later years. Roger Bingham of TSN will coordinate these efforts.

6) Translational activities: We will begin to show translation of our science to education through further development of the “Let’s Face It!” and RUBI projects.
Year One Project: Let's Face It :PEN Translation Project. Project Leaders: Tanaka and Schultz.

An emerging body of research indicates that children with autism spectrum disorder show selective deficits in face recognition. Therefore, it should not be surprising that they 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? 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 and other social learning deficits. 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 Scientific Learning Corporation’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 neurological function. With respect to the question of temporal dynamics of learning, the LFI! platform addresses temporal change over a relatively long period of time. That is, the intervention examines the behavioral plasticity of face processing occurring over a time scale of weeks, if not months of training and practice. In this treatment program, long-term learning is measured by the child's pre- and post-training performance on the Victoria/Yale Face Processing Battery. The battery is not only used to evaluate the efficacy of the intervention, but more importantly, the pre-training assessment provides critical diagnostic information for guiding subsequent face processing treatment.

Year Two Project: The RUBI Project: SIN Translation Project. Project Leader: Movellan.

The RUBI project is developing a robot with a three degree of freedom head, two arms, and a touchscreen. The actuators consist of a 12 inch touch video screen, 3 speakers, and 13 servo motors to control the neck, cameras, and facial expressions. The robot will be powered by a cluster of 4 computers connected via high-speed Ethernet. Following the philosophy of the RUBI project, we propose to immerse the robot and researchers one hour a day at the Early Childhood Education Center and the Preuss School. The performance of the robot will focus on two basic metrics: (1) goodness of the interaction and (2) learning effectiveness. One of the issues at hand will be to investigate how the one-on-one personal tutoring provided by the robot platform compares with a traditional computer tutoring system, and with human tutoring.

INITIATIVE 7. Diversity
(Initiative Coordinator: Gary Cottrell)

In terms of including more minority faculty in our Center, we have identified and will continue to identify minority junior faculty from other institutions who we will ask to participate in appropriate network meetings. In terms of graduate students and postdocs, we will use the considerable diversity already existing at Rutgers Newark to attempt to recruit diverse graduate students and postdocs to our Center labs. We do not have enough funds in any one project to pay for a postdoc, but we have two minority graduate fellowships promised to us from our Vice Chancellor of Research at UCSD that will be useful for this purpose. We will also suggest
scholars for the Minority Research Seminar series at Vanderbilt as a mechanism to introduce minority faculty to our program.

Our plans for recruiting minority graduate students include the Faculty Partners Program, a mechanism intended to help us form relationships with faculty at minority serving institutions. In California, there are a large number of minority serving institutions in the form of the state university system, and in neighboring states, there are a large number of Hispanic serving institutions. We will first concentrate our efforts on these by traveling there and giving talks in order to meet the faculty, for the purpose of inviting them for a two-day visit to our Center. It is through personal relationships that faculty at these institutions will begin to encourage their students to apply to us for graduate school.

Our plans for recruiting minority undergraduates center on two aspects of our program: 1) our partnership with the Preuss school, a 72% underrepresented minority serving charter school on campus, and 2) the Reach for Tomorrow program, which brings inner city and other minority high school students to UCSD (and other campuses) for an intensive one to two week program. Our plans are to work with the Preuss principal, Doris Alvarez, a member of our Executive Committee, to expand the number of Preuss students who are either in our labs or mentored by members of our center.

**Timeline, Milestones, and Resource Allocation:**
None of the faculty and graduate student recruiting plans require a great deal of money, except the Faculty Partners Program. We expect this to cost on the order of $10,000, which we will allocate in the first year, with the intention of having one iteration of the program occur within the first eighteen months. We will also allocate $10,000 for Reach for Tomorrow to encourage more students to come to UCSD in the summer of 2007, with more allocated in Year 2. If time allows, we will consider submitting an REU Site proposal with a significant diversity component. However, this may require building relationships with minority-serving institutions first, in order to include them as partners in the REU.

**Milestones** will include initiating the Faculty Partners Program by making at least two trips to minority-serving institutions in order to begin developing relationships with appropriate faculty. We aim to invite half a dozen faculty from minority-serving institutions by the fall of 2007. A second milestone will be subsidizing at least five more minority high school students to come for the summer 2007 Reach for Tomorrow program on the UCSD campus. A third milestone will be to include at least two more students from the Preuss School in UCSD labs. A fourth milestone will be the attendance of at least two minority faculty to research network meetings. A fifth milestone is the awarding of at least one San Diego Fellowship in the spring year 2. We feel that we do not have the web presence yet to expect to have much interest in the Center in this academic year.

**INITIATIVE 8. Implementing, Documenting, Disseminating, and Evaluating the Network of Networks Paradigm for Scientific Inquiry**
(Initiative Coordinators: Gauthier and Palmeri)

The detailed implementation plan is included as part of Initiative 8.
**Timeline and Milestones:**
In the first year of the center, one of our primary goals will be to develop the three new research networks. Much of this work has been ongoing for the past six months as we have prepared for the official start of the center. As part of the all-center meeting in January, the research networks will work together to establish a common set of expectations for the members of the networks with guidance by members of the PEN network. Over the coming year, each Network will have monthly meetings. At least one of these meetings will be a two-day workshop in which members travel to meet, share data, and exchange ideas. Each of the Network leaders will be responsible for planning the agenda for meetings. The Program Representative will be responsible for planning the dates and details of the meetings. The Science Network will document the formative stages of the development of these new research networks. Surveys will be conducted by our external evaluators in order to establish Year 0 data (prior to the development of our center proposal) and Year 1 data (current) on the collaborative relationships among center investigators.

As a first step in dissemination, we plan to submit a conference symposia organized around topics having to do with scientific collaboration. How does scientific collaboration emerge naturally and how can collaborative research structures like ours significantly accelerate new scientific discovery? Specifically, we plan to submit a proposal to the 2007 meeting of the Cognitive Science Society to be held in Nashville, TN.

**Resource Allocations:**
Each network will be allocated 10K for travel to meetings in order to facilitate interactions and scientific synergy amongst network investigators. Every network member will also attend the Center All-Hands Meeting (at which time networks will be allocated some meeting time, alongside strand and initiative meetings). $45,920 will be allocated for the All-Hands Meeting.
SECTION IV: Management Structure and Plan

The Temporal Dynamics of Learning Center management is structured with strong leadership that will be the shared responsibility of the Center Director (PI) and two Center Co-Directors (Center Director for Science and Center Director for Outreach). These Directors of the Center will provide the vision for the Center, sunset ideas that aren’t working, and resolve any conflicts that arise. The Executive Committee, comprised of a balanced, diverse, and skilled set of Center leaders, will provide shared governance, with primary management for individual research networks coming from the local leader of each unit. External advice on Center management will be provided by the External Advisory Board, as well as management and evaluation consultants, ensuring the fine-tuning and absolute success of the Center. An organization chart summarizing the Center’s management structure is shown above.

Internal Center Management:

Primary Center Directors:
Center Director (PI): Gary Cottrell
Center Director for Outreach: Terry Sejnowski
Center Director for Science: Andrea Chiba
Executive Committee:
Doris Alvarez
Mark Appelbaum
Roger Bingham
Andrea Chiba
Gary Cottrell
Daniel Feldman
Isabel Gauthier
Javier Movellan
Thomas Palmeri
Terry Sejnowski
Paula Tallal
Administrative Director (non-voting staff representative)
Program Representative (non-voting staff representative)

Management Staff:
Administrative Director (full-time)
Program Representative (full-time)
Fiscal Officer/Budget Specialist (part-time)
Administrative Assistant (full-time)
Webmaster (part-time)

Network Co-PIs:
Daniel Feldman: Network Co-PI (Sensorimotor Network)
Andrea Chiba: Network Co-PI (Interacting Memory Systems Network)
Thomas Palmeri and Isabel Gauthier: Network Co-PIs (Perceptual Expertise Network)
Javier Movellan: Network Co-PI (Social Interactions Network)

Resource Directors:
Doris Alvarez: Principal (The Preuss School)
Mark Appelbaum and Reagan Moore: Co-Directors (Data-sharing Facility)
Roger Bingham: Director (The Science Network)
Scott Makeig: Director (Brain Dynamics Facility)
Terry Sejnowski and Paula Tallal: Co-Directors (Education and Outreach Center)
Emo Todorov and Howard Poizner: Co-Directors (Motion Capture Facility)

Initiative Coordinators:
Dan Feldman and Paula Tallal (Initiative 1)
Andrea Chiba and Isabel Gauthier (Initiative 2)
Javier Movellan and Emo Todorov (Initiative 3)
Terry Sejnowski, Thomas Palmeri and Tony Bell (Initiative 4)
Scott Makeig, Javier Movellan, Emo Todorov (Initiative 5)
Terry Sejnowski and Paula Tallal (Initiative 6)
Gary Cottrell (Initiative 7)
Isabel Gauthier and Thomas Palmeri (Initiative 8)
**External Center Management:**

**External Advisory Board:**
- James McClelland (Stanford University) (Chair)
- Sue Becker (McMaster University) (Vice-Chair)
- Peter Dayan (University College London)
- Robert Goldstone (Indiana University)
- Annette Karmiloff-Smith (University College London)
- Mark Mayford (The Scripps Research Institute)
- Janet Metcalfe (Columbia University)
- Wolf Singer (Max Planck Institute for Brain Research, Frankfurt)
- Richard Sutton (University of Alberta).

**External Evaluator:**
- Brenda Turnbull (Policy Studies Associates)

**Evaluation Consultant:**
- Andy Porter (Director of the Learning Sciences Institute, Vanderbilt University)

**Temporal Dynamics of Learning Center Leadership**

**Role of Center Director/PI (Gary Cottrell):**
The Center Director (PI) will be responsible for guiding the Executive Committee in building and maintaining a cohesive vision for the Temporal Dynamics of Learning Center. The PI will be responsible for leading Director, Executive Committee, and Center Meetings. The PI will oversee and structure the Center Staff in managing the day-to-day operations of the Center. The PI will have ultimate responsibility for final reporting functions of the Center. The PI will be the primary contact and facilitator with the External Advisory Board, the NSF, and the Directors of other NSF Science of Learning Centers. (Gary Cottrell will serve as PI with Terry Sejnowski as primary alternate and Andrea Chiba as secondary alternate.)

**Role of the Center Director for Science (Andrea Chiba):**
The Center Director for Science will be responsible for communicating with the Network Co-PIs to ensure that the individual research networks are functioning fluidly in attaining their goals. The Center Director for Science will be responsible for coordinating activities between the Network Co-PIs and the Data-Sharing Facility Co-Directors to establish a GRID Development Team, ensuring the utility of the Data GRID for all Center participants. The Center Director for Science will work with the Data-Sharing Facility to ensure that the Research Network Participants are meeting their target goals for entering data and required reporting paperwork. The Center Director for Science will communicate regularly with the Network Co-PIs in assessing and planning for future scientific needs of the Research Networks (theoretical and technical). The Center Director for Science will communicate with the Network Co-PIs to ensure that the Cross-Cutting Facilities are meeting the needs of the network scientists. The Center Director for Science will be responsible for planning and leading quarterly group meetings with the Network Co-PIs. The Center Director for Science will assist the PI in managing the Center.
during heavy activity periods. In the absence of the PI, the Center Director for Science will serve as “Acting PI” in overseeing the Center Staff in managing the day-to-day operations of the Center. (Andrea Chiba will serve as Center Director for Science with Daniel Feldman as primary alternate.)

**Role of the Center Director for Outreach (Terry Sejnowski):**
The Center Director for Outreach will be responsible for communicating with the Outreach Center, the Science Directors, and CALIT2 Staff to ensure that translation is being facilitated and that translational target goals are being met. The Center Director for Outreach will monitor Center activities for the purpose of alerting local and national press to significant findings by center investigators. Working closely with the PI, the Center Director for Science, and the Executive Committee, the Center Director for Outreach will have the ultimate responsibility for and primary leadership of any necessary Research Network or management restructuring undertakings (including, but not limited to, replacement of research personnel or research networks). The rationale for this is that the Outreach Director will have the least conflict of interest in implementing these decisions. In the absence of the PI, the Co-Director will be available to serve as a secondary contact or facilitator with the External Advisory Board, the NSF, and the Directors of other NSF Science of Learning Centers. (Terry Sejnowski will serve as Center Director for Outreach with Paula Tallal as primary alternate).

**The Combined role of the Center Director (PI) and Center Co-Directors:**
The three Primary Center Directors (the Center Director/PI, the Center Director for Outreach, and the Center Director for Science) will be responsible for submitting proposals to the Executive Committee for modifications and/or growth of the Center. The three Center Directors will be empowered to resolve any disputes that arise (and will do so through democratic process amongst the three). The three Center Directors hold veto power over Executive Committee initiatives that may not be in the best interest of the larger Center. The Executive Committee will have recourse by a formal written appeal to the Advisory Board Chair as described below. The Primary Center Directors will meet quarterly and on as-needed basis, in order to aid in guiding the direction and management of the Center.

**The Role of the Executive Committee:**
The Executive Committee is the primary governing body of the Temporal Dynamics of Learning Center and operates through the democratic process of its voting members. The Executive Committee will be responsible for working with the Center Director to maintain a shared vision for the Center. Towards this end, the Committee will be responsible for voting on and planning growth and restructuring initiatives for the center. The Executive Committee will oversee the distribution and utilization of research funds to the four Research Networks, the Education and Outreach Center, and the three Cross-Cutting Research Facilities. 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 appoint a Diversity Subcommittee Task Force for seeking out postdoctoral fellows for our Minority Postdoctoral Fellows Program and minority scholars for our Visiting Minority Scholars Program. The Executive Committee will evaluate how well the Center is achieving its goals for diversity through the inclusion of men and women, under-represented 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 Research Networks are achieving the broad Center goal of building dense interconnections of collaborations within each Research Network and across Research 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 be responsible for bringing any Center disputes to the attention of the Center Directors for resolution. In the event that the Executive Committee has an irreconcilable grievance with the Center Directors, the Executive Committee will have the authority to appoint a spokesperson to contact the Chair of the External Advisory Board (who will contact the Vice-Chair) for guidance and arbitration. Alternatively, this process can be achieved through a letter to the External Advisory Board members. The Executive Committee will meet quarterly and more frequently when need arises. For example, we expect there will be meetings at least every two weeks in the initial months of the Center.

The Executive Committee will depend on its External Advisory Board for an independent evaluation of how well the Temporal Dynamics of 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.

Role of the Network Co-PIs:
The Network Co-PIs will oversee the ongoing operations of their Research Networks. The Network Co-PIs will be responsible for communicating with their network members regarding all Center goals. The Network Co-PI can serve as an initial liaison between Network researchers and, if needed, as a collaboration facilitator. The Network Co-PI will be responsible (with the support of the Center Staff) for planning and leading the biannual Network Meetings. The Network Co-PI will be responsible for communicating any potential Network problems to the Executive Committee. The Network Co-PI will be responsible for guiding their Research Network in undertaking cross-network collaborations towards the goals of the Center. The Network Co-PI will be responsible for the compilation and final submission of the Research Network yearly progress report on activities (documenting publications, complementary grant funding, awards, and other notable Research Network results). The Network Co-PI will be responsible for participating in quarterly Research Network Co-PI meetings. Each Network Co-PI must also serve on the Executive Committee.

Role of the Resource Directors:
The Resource Directors are each responsible for overseeing the general operation of their resource. The Resource Director is responsible for compiling and submitting the yearly report on the activities, progress, and accomplishments of their resource. The Resource Directors are responsible for ensuring that their resource is reaching targeted goals and adequately serving the Center. Resource Directors are responsible for guiding and overseeing the project staff associated with their resource. The Resource Directors are responsible for communicating progress and problems of the resources to the Executive Committee. A Resource Director may be asked to serve on the Executive Committee.

Education and Outreach Center Co-Director Paula Tallal will serve on the Executive Committee. Her wealth of experience and success in translation of basic science to education and her history
of initiating and managing a center provide a valuable resource for the Executive Committee. Data Sharing Facility Co-Director Mark Appelbaum also serves on the Executive Committee. His presence on the Executive Committee is of exceptional value due to his wealth of experience in management oversight of large, interdisciplinary centers and the critical importance of this Resource to the Center’s success. Furthermore, the Data Sharing Facility is a unique feature of our Center and it is necessary to have a representative of this facility on the Executive Committee. Similarly, The Science Network is crucial to our outreach to the public, hence we include its Director, Roger Bingham, on the Executive Committee. Finally, Doris Alvarez, Principal of the Preuss School, is included due to the central role the Preuss will play as our living laboratory and in the recruitment of diverse undergraduates.

**Role of Initiative Coordinators:**
Research in the Center will be organized around four scientific initiatives. The goals of each initiative are inherently cross-disciplinary, and will require coordinated research by all four research networks. Thus, the members of the research networks associated with each initiative will also meet together on a regular basis in “Initiative Meetings” to synchronize their research around these Center Initiatives. The Initiative Coordinators will lead those meetings and report results to the Executive Committee. The Center has also defined four additional center initiatives on technologies for the science of learning, integration of research and education, diversity, and developing the Network of Networks organization. The Initiative Coordinators will oversee and coordinate those large-scale initiatives and report results to the Executive Committee.

**Role of the External Advisory Board:**
The External Advisory Board’s role is to provide an independent evaluation of how well the Temporal Dynamics of Learning Center is achieving its research, training, education, and outreach goals. The External Advisory Board will provide guidance for adjusting Center priorities, in order to address important scientific, education, workforce, and national security priorities. The Advisory Board 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. The Annual Center Meeting will be scheduled to coincide with the Annual Advisory Board meeting, in order to maximize opportunities for members of the Board to see the outcomes of the Center. During the first year, the Center Directors will work closely with the External Advisory Board and the Evaluation Consultant to establish the rubrics to be used for evaluating and assessing the Center. Thereafter, the main goal of the Advisory Board will be to serve as a third party evaluator for the review of Center progress, direction, and leadership. The Chair of the External Advisory Board may be called upon to arbitrate between the Center Directors and the Executive Committee, in the extreme case that there exists an irreconcilable dispute or grievance. The Chair of the External Advisory Board is Jay McClelland, with Sue Becker Serving as the Vice Chair. Jay McClelland has a prodigious record of building and running large centers, as well as being a leader of several prestigious scientific boards. Sue Becker has a diverse scientific background and has served in many leadership roles, including serving on executive board for the Neural Information Processing Systems Foundation and a member of the 5-year review committee for the RIKEN computational neuroscience laboratories.
**Role of the External Evaluator:**
The External Evaluator (Brenda Turnbull, Policy Studies Associates) will provide qualitative and quantitative assessments of all the Center activities. The External Evaluator will be responsible for developing and administering assessment tools to all relevant parties and for analysis and comprehensive reporting of the assessments. The External Evaluator will work closely with the External Evaluators at other NSF Science of Learning Centers to develop a common set of evaluation instruments and metrics. The External Evaluator will provide final recommendations for the Center, based on the comprehensive report. We will also look to our External Evaluation Consultant (Andy Porter, Learning Sciences Institute, Vanderbilt University) for further advice on evaluation metrics and evaluation procedures; Andy Porter has extensive experience with large NSF and IES center grants as well as heading learning sciences centers at Wisconsin and Vanderbilt.

**Center Management Staff**
The PI will establish the roles of each of the Center management staff to best facilitate the operational, fiscal, and project needs of the Center, while best utilizing the skills of the Center’s staff. The Temporal Dynamics of Learning Center will be staffed by an Administrative Director, a Program Representative, a Fiscal Officer/Budget Specialist (part time), an Administrative Assistant, and a Web programmer (part time). In addition to the primary Center Management Staff, CALIT2 (California Institute of Telecommunications and Information Technology, where our Center will be physically housed) has offered the Center flexible staff allocation, such that skilled staff can be reserved and added to the Center during periods of specific need. For example, during periods of boot camps and workshops, an additional event-planning staff member can be allocated and during fiscal closing periods, an additional fiscal staff member can be allocated. CALIT2 developed this flexible management system in order to best meet and support the needs of its scientists, while maintaining a lean fiscal system. Thus, long-range planning will include additional staff allocations during specific periods.

**Role of the Administrative Director (AD):**
Under the general direction of the Center’s Directors and the Executive Committee, the Administrative Director will have executive responsibility for day-to-day project management, staffing, and resource allocation for the Center. The AD will also initiate, plan, develop and review the strategic management plan for the Center in cooperation with the Executive Committee. The AD will develop center policy and procedures within the framework of NSF requirements, be the primary administrative liaison between funding agencies, research groups and facilities, and outreach partners. The AD will oversee the outreach programs, fund raising, public relations, and program planning. The AD will create the annual operating budget for the Center and provide financial oversight to projects and facilities.

**Role of the Program Representative (PR):**
Under the general direction of the Center’s Research Directors and the AD, the Program Representative will organize all Center meetings, meetings of Research Networks (except for PEN), Initiative/Strand Meetings, Modeler’s meetings, etc. The PR will also organize the boot camps for researchers, graduate students, and undergraduates. The PR will oversee the Web Programmer to ensure that the web site is kept up to date with current activities, results, and center news. Given the current funding restrictions, the PR will also work on outreach issues for the center, ensuring that news of positions at our center are broadly disseminated, coordinating
the Faculty Partners Program, interfacing with Reach For Tomorrow, the Preuss School, and other outreach partners.

Role of the Administrative Assistant:
The administrative assistant will aid the Center Director, the AD and the PR in carrying out their duties.

Role of the Fiscal Officer / Budget Specialist:
The fiscal officer / budget specialist will perform post-award administration and reporting, create budgets as the funding profile changes, ensure that all monies are spent in accordance with NSF and UCSD guidelines, and interface with partner institutions on sub-contracts.

Role of the Web Programmer:
The web programmer will design and implement the Center Web sites, and maintain them with up to date information about the center.
SECTION V: Evaluation Plan

Our evaluation plan is being developed and coordinated by our third party external evaluators, Brenda Turnbull and colleagues from Policy Studies Associates, Washington, DC. They are working closely with a Subcommittee for Evaluation composed of members of the center’s Executive Committee and with our evaluation consultant, Andy Porter, Director of the Learning Sciences Institute at Vanderbilt University. Our external advisory board is also an important part of our center evaluation; they will provide a critical eye to both the products and the process of the center. The final evaluation plan will meet the standards established by NSF and will provide the critical information of most use to the Directors and the Executive Committee of our center.

Broadly speaking, we see this evaluation as meeting two general objectives: One objective is demonstrating the value added by a center mode of funding. Is the center creating a collaborative environment? To what extent do center members collaborate across disciplines, laboratories, and networks? What is the intellectual and professional value of center participation to member investigators, postdoctoral fellows, and students? To what extent do center investigators, postdocs, and students use the Cross-Cutting Resources of the center? To what extent have the network-of-networks structure and the availability of the Cross-Cutting Resources influenced the practice of science (formulation of research questions and agendas, communication and collaboration within and across networks, practices in sharing data and reporting results)? Is the center environment producing advances in research, education, outreach, and translation that would not have happened or would have happened more slowly without the center? Has the center created new research and training programs for graduate and undergraduate students as planned? Has the center carried out its planned activities in recruiting new graduate and undergraduate students from diverse populations? What are the outcomes of the training and outreach activities that the center supports?

The other objective is providing important feedback to the Center Directors and the Executive Committee about how the center operates. Is the center meeting its objectives and goals? Does the center have open lines of communication? Does the center have the right training, outreach, and diversity plan? Are center operations perceived as efficient and effective?

We will now briefly summarize some of the various metrics we plan to use in our evaluation. We should note that the evaluation plan is still evolving. The third party evaluators for all of the centers have only recently begun to set up something akin to a network of evaluators with the aim of sharing evaluation metrics and possibly establishing some common evaluation instruments that will be used by all of the NSF Science of Learning Centers. Hence this evaluation plan is likely to evolve as the network of centers begins to coordinate their activities.

In general our evaluation metrics will include a combination of quantitative data, surveys, and case studies. A key challenge is documenting the value added by our center. One way we will assess this is by comparing the values of various metrics before we developed our center proposal to the values of those metrics each year of the center; for example, how has the network of collaborative research projects grown each year of the center? We will also attempt to compare the values of these metrics to a suitable comparison group of investigators not involved in a center such as ours; for example, how does our pattern of collaboration compare to a similar group of scientists who are not part of such a collaborative center? Our evaluation plan will scale
up as our funding grows from years one through three of the center. We focus here on our evaluation plans for year one.

Evaluating our Science. Our aim is to advance our knowledge and understanding of the temporal dynamics of learning. From the start of the center, we will keep detailed records of publications in top scientific journals and presentations at important national and international conferences. In later years of the center, we will examine citations to research supported by the center. Because the center cannot possibly support fully all of the research it fosters – especially expensive research like neurophysiology and functional brain imaging – we will also record grant proposals submitted based on work originally supported by the center. We fully expect that new collaborative projects spawned by the center will look to independent sources of funding, especially given the small center budgets in years one and two. Mark Appelbaum will lead our efforts to create a web-based interface to our databases to make it easy for center investigators to regularly update publications, presentations, grants and other activities related to the center.

These quantitative measures will be supplemented by surveys of the center investigators, guests to network meetings, and executive committee members that will ask about the importance and impact of the research supported by the center. Eventually, we will also use case studies to spotlight scientific advances supported by the center. The PEN network used this case study approach in one of its progress reports to the McDonnell Foundation a few years ago: They highlighted a series of publications involving over a dozen investigators and trainees that tested individuals with prosopagnosia, autism, and Asperger’s syndrome using behavior measures and adapting fMRI tasks that were developed in earlier work by PEN investigators to study perceptual expertise.

Evaluating our Collaborative Environment. The center will be successful if we create collaborative teams of researchers approaching a new understanding of the temporal dynamics of learning from multiple perspectives using multiple techniques. 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 novel interactions between researchers from different disciplines, causing a new synthesis from old parts.

While precisely quantifying how well we achieve such lofty goals is difficult, the importance of our aim of synchronized research requires that we measure our success in achieving it. Thus, the external evaluators and the Executive Committee will develop indicators of synchronized research, and surveys will be used to assess the extent to which research within each research initiative is synchronized. We will also ask investigators to report on the extent to which they are experiencing conceptual collisions in their center work, and on their advances in knowledge synthesis.

In addition, documenting the number of collaborative projects and publications has proved one useful metric for evaluating the previous success of PEN, an approach that we will adopt in the center. Members of PEN had just a few collaborations before the network formed. Over the years, it saw the growth of several dozen collaborative projects, each involving multiple PEN investigators and their trainees. We will measure the growth of such collaborative projects within PEN and each of the three new research networks and will measure the growth of cross-network collaborations between networks as well. We should note that in some cases, center investigators may adopt competing perspectives on learning, so we will encourage those investigators to seek scientific outlets that promote a point-counterpoint style of discourse as well.
As noted above, we will eventually use case studies as tools to document the outputs of the collaborative structure created by the center. Because case studies can be relatively expensive, we will use this method only to study collaborative relationships that appear particularly productive and that seem unlikely to have emerged without the center structure. Case studies will document how collaborative relationships developed and how they result in integrated or synchronized research. While these case studies will become parts of the annual reports in our center evaluation, we will only do them if they also have a place in a publication for public consumption as well, such as a review article by center investigators.

In addition to documenting collaborative projects, we will also document the growth of other forms of interaction and influence within and across networks in the center. While everyone in the center knows someone, no one in the center knows everyone. Using surveys, we will ask all center investigators to rate how well they know the research of every other center investigator, the extent to which the research of every other center investigator has influenced their own research, and the extent (if any) to which they collaborate with every other center investigator. For those with whom they do collaborate, surveys will ask about the frequency of interaction, the types of collaboration in which they are engaged (e.g., refereed journal article, instrument design/development, field project design/development), and the intellectual outcomes of the collaboration (e.g., whether the other individual’s thinking “advanced my thinking, sharpened my thinking in new ways” or whether “the results of our collaboration challenge prevailing paradigms and/or practices by proposing new alternatives” (items drawn from an evaluation of scientific collaboration conducted by Diana Rhoten, who has shared her instruments with the SLC evaluators). We will also use citation counts to document the growth of influence among center members that may not be reflected in active collaborations. Our surveys will also ask center investigators whether collaborating has produced novel results, has changed the way they think about their research, has challenged prevailing paradigms and practices, and changed the way they teach. Finally, we will document use of the data sharing facility, noting which collaborative projects and individual investigators share data and how often that data is access, analyzed, and annotated.

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 and survey investigators on their use and operation, in order to invest or divest in resources according to their use and impact. We will also survey investigators on their use and their operation. In addition, we will set up mechanisms for center investigators to recommend investments in new cross-cutting resources.

On an annual basis, the measures of the science, and the collaborative environment, and investments in resources will be used to make strategic decisions regarding center funding for future research. Research networks that are not operating as collaborative environments will develop a plan to change their activities and may eventually be disbanded or significantly reorganized. The evaluation will also document these aspects of center management.

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 rather than by 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 faculty and postdoctoral positions at top tier universities. In the
Perceptual Expertise Network, our most successful trainees have been those who have published papers with multiple PEN investigators and other PEN trainees. We have also found that feedback forms from the graduate 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, Outreach, and Translation. The center will be successful if we develop 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.

The evaluation will describe our most intensive interactions with these potential constituencies and partners, gathering and assessing the evidence that bi-directional communication has been established. In the longer term, we will know that we are successful if these reiterative interactions from the science to education and outreach and back to the science lead to much more rapid translation of our research into practical application in the classroom and other educational setting, and data taken directly from student’s learning in the classroom becomes rapidly integrated into our research. Translations from science to practice supported by the center will be rigorously evaluated using experimental and quasi-experimental evaluation techniques.

Evaluating our Diversity. We will monitor the gender and racial composition of the center, from senior investigators through graduate students, through undergraduates and high school students. Even with the significantly reduced budget in years one and two, we will increase our involvement in The Preuss School, both by bringing students from underrepresented minorities into our laboratories and by having center investigators do outreach in the school. We will also make modest investments in Reach for Tomorrow. While the outcomes of this direct investment won’t be known until these children make decisions to pursue STEM disciplines in college, we can look to previous success of Reach for Tomorrow in encouraging at-risk youth to pursue science and technology for encouragement that this modest investment will be worthwhile. Finally, we will make a modest investment in the faculty partners program. We will evaluate its success through surveys and by tallying the numbers of students of these faculty partners who apply to our graduate programs for advanced training. Eventually, these surveys will be supplemented by case studies of students and faculty whose participation in these various programs appears to have been significant in their careers.