CONSOLIDATION AND LEARNING: A CONNECTIONIST MODEL OF HUMAN CREDIT ASSIGNMENT

by

Eric Lance Chown

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Doctoral Committee:

Professor Stephen Kaplan, Chair
Professor John Holland
Associate Professor John Laird
Associate Professor Barbara Therrien

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To My Parents,

Donald and Janet Chown.

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CHAPTER 1

INTRODUCTION

This dissertation is about human learning, but more specifically aspect impacted by credit assignment, such as why learning is effective in some cas others. Many of the techniques traditionally used in artificial intelligence an connectionism have been tailored to specific circumstances and do not apply spectrum of human learning. Domain knowledge, such as is used in explana learning, is not always available, for example, nor are the teaching signals us propagation systems. Learning is a difficult challenge under any circumstan task is made even harder when prior knowledge and models cannot be appli that a comprehensive learning theory must not only be able to effectively us but also must first be able to bootstrap itself up in situations where there is l knowledge available. Credit assignment is fundamentally about learning wh caused other events to happen, a daunting task without usable knowledge. (hand, humans, especially children, certainly learn about new domains and a reasonably efficiently.

The point of view of this dissertation is that to a large extent the succes learning is due to the fact that there are a variety of techniques which are ge and can serve in the bootstrapping process. While the world is an extremely it is not without structure, often structure that repeats from domain to dom organism which is particularly sensitive to such structures would have a clea advantage over those which are not. To some degree this dissertation is an those structures and sensitivities, and an analysis of the mechanisms inherer brain that code them.

Insight into these sensitivities is provided by an examination of the cor process, a brief period of transition during which memory is fixed or made p There is a large set of evidence linking consolidation with the ultimate streng Consolidation is modelled in this dissertation using TRACE (for Tracing Recu in Cognitive Elements), a connectionist simulation based upon Hebb's cell as construct. Learning in TRACE comes as the result of correlated neural activit which influence such activity, therefore, will necessarily impact learning. Th the human cognitive architecture with the sensitivity required by the learnin

The conjecture that humans are predisposed to be sensitive to certain l information and environmental structure is contrary to the "blank slate" and proposals (Midgley, 1978); this is not to say, however, that the slate is not b that some things are particularly easy to write, while other are quite difficult learning terms this means that human learning is biased in certain ways. Th based systems often used in artificial intelligence, by contrast, tend to favor a approach where one piece of information is no different than any other. Th often seem to contain biases, but these biases typically come in the form of t knowledge that such systems start out with. Where information gains impor an approach is through its use. A rational approach would hypothesize that especially interested in snakes it is probably because they are aware of how s and of what they are capable. This also tends to be true of the symbol syster intelligence; there is nothing special about a symbol in and of itself, indeed i nature of symbols that they can be processed in virtually any desired way, a be argued that symbols are useful precisely because they can be manipulated fashion (Newell, 1990).

By contrast an organism which is highly sensitive to certain generic env structures and information may lose some of its flexibility, at least theoretica gain in its ability to cope with new environments. A theory based upon such would conclude, for example, that people are interested in snakes in a way tl hardwired as the result of evolution. In particular, snakes are an arousing st result of the increased levels of arousal involved when humans see a snake is in such a situation will tend to be stronger than normal. From an adaptive p is even possible to see how this might come about as the result of natural sel treating snakes differently affords some type of adaptive advantage those or treat snakes in such a fashion are more likely to survive and reproduce. Suc need not be born with knowledge of snakes; it may be enough that they are objects which move along the ground, along with a predisposition to treat su caution.

Arousal is one of the key factors which impacts consolidation and will l throughout the dissertation. The relationship between arousal and the stren is well known (Kleinsmith and Kaplan, 1963): When arousal is high, learnin when arousal is low, learning is weak.

Consider the differences in how the two different types of systems mig the sight of a snake. A purely rational system would check on what it knows to come to a conclusion about how to act. A system sensitive to the kinds of provided by snakes, on the other hand, would automatically react with heigh (and probably caution), high levels of arousal, and then, if knowledge were a further direct its actions, it would behave accordingly. The advantages of a s type are that it behaves in what should be a reasonable fashion even when th information available, and that its first reaction is swift and does not rely up deliberation, an important advantage when speed is of the essence. Many ar intelligence systems can gain this speed by compiling knowledge, but this sti address the issue of how to behave when knowledge is not present. Further, levels of arousal associated with such an encounter also ensure that the situa well learned such that the knowlegde gained can be used in the future.

The previous example highlights some of the important points that will emphasized throughout this dissertation as being critical in learning. First, a is sensitive to important stimuli and generic environmental structures is cons important ways. One such way is behaviorally; it might not be possible to ig for example. A more important type of constraint with regard to this disserta the form of functional constraints imposed upon the system by its physical in A major theme of this dissertation is that the underlying physical properties the"symbols" in the human cognitive architecture play a major role not only but in learning as well. Further, ignoring these properties may handicap lea so severely that they will be unable to easily account for certain kinds of data

This relationship between the properties of the symbols and their impa behavior will most clearly be seen through an examination of arousal. High l arousal have been shown to result in "reminiscence," a situation where perfo improves over time without intervening practice. In this case high levels of a impair short term recall. This result is counter-intuitive, seemingly maladapt now has never been successfully modelled. Reminiscence can be modelled in within the context of a consolidation-based learning system, the effects can a to be adaptive. Further, the ability to model reminiscence in TRACE stems di the constraints derived by its grounding in a neural architecture.

Another theme in the dissertation, and one closely related to consolida temporal, not in the sense of fast reactions (though that is certainly importa the sense that the timing of events can play a large role in learning. Unfortu been all but ignored in the majority of connectionist systems and while it is r thoroughly addressed in symbolic systems, there are still problems with the approach. Connectionist network representations such as feed-forward netv Hopfield networks are little more than stimulus-response systems of the kinc the behaviorists (Kaplan et al., 1990). The state-space representations used artificial intelligence systems, on the other hand, provide a fairly natural way temporal information. According to the Handbook of Artificial Intelligence (I Feigenbaum, 1981) “A state-space representation of a problem employs two (*states*, which are data structures giving ‘snapshots’ of the condition of the pro stage of its solution, and *operators*, which are means for transforming the prob one state to another.” Transitions between states come as the result of opera make specific, and generally predictable, changes to the world. The flow of t represented as a series of states with operators causing transitions along the with knowledge of how the operators work, an AI system can search the spac states in order to solve problems or make predictions.

The state-space idea is very appealing because it cuts the world up into pieces; however, the way in which it does so can cause important informatic State-space representations of the world are static; each state is a snapshot. are static they are sensitive to ordering information, but not necessarily to ti representation of an environment changing from one state to another is the s of the time interval involved. While timing information could be coded as an state or operator representation such an addition is not flexible or natural.

By contrast, in a system where data has dynamic relationships, timing can be automatically coded into the relationships. Cell assembly models, suc are examples of such dynamic representational systems. Cell assemblies are connectionist "symbol," consisting of a collection of tightly interconnected n Perception of an object in a cell assembly model comes in the form of the act corresponding cell assembly. Cell assemblies are not controlled by an extern rather tend to be activated either by direct environmental stimulation or assc other cell assemblies. One of the primary modes of learning in a system of c therefore, is sequential, in order to recreate temporal series.

One difficulty with such a dynamic representation is control. State-spa representations are useful primarily because they are easily manipulated; ch can, for example, look ahead at billions of moves in the space of seconds. Dy representations appear to be much more limited because a controlling progra available to iterate through possible states. Among other things, this lack of that a dynamic system can get "off the track," a situation akin to wandering a While this may seem reasonable when modelling human performance, it is no desirable from the point of view of a computer model designed to perform a Nevertheless, humans do have the capability, for example, to pay attention e of distractions. This implies that dynamic systems must also have control m available, though such mechanisms are likely to be dynamic themselves. Thi TRACE stems from the larger cognitive architecture, called SESAME (for the S Environmentally Sensitive Adaptive Mechanisms), in which TRACE is embedd SESAME contains a number of control mechanisms, discussed in Chapters 5 a including several which impact attention.

One of the outcomes of the differences between dynamic and static rep comes in the nature of what is learned. Ostensibly both systems are learning however the nature of the modelling is subtly different. A system using a sta representation learns about operators: what they are, when to apply them, w effects are. This type of learning could be termed "causal" because it involve what causes the world to change. A dynamic representation, on the other ha purely sequential, learning sequences even when the world appears to be sta

The advantage of emphasizing pure sequence over causal relationships learning sequences requires little or no analysis. Further, causal relationshi derived from sequences, and in a world where actions are often immediately their consequences, learning a sequence is often sufficient to learn operators the possibility that an approach emphasizing sequence will not be effective w not immediately followed by consequences, a subject that will be discussed in Chapter 3. It further raises the question of the effects of previous knowledg is learning sequential information, it is not obvious how prior knowledge can make learning more efficient. This occurs in several ways in TRACE. First, tl learning is to change the internal structure of cell assemblies; these changes subsequent processing and, therefore, learning. Further, the SESAME archite sensitive to clarity and confusion, states which code relationships between p and the current state of the world. In turn, these sensitivities, as with others architecture, feed back into the learning system through the consolidation m

TRACE is a cell assembly model which purports to be able to account fc consolidation and the relevant sensitivities involved. Successfully modelling sensitivities is difficult for several reasons, each of which will be dealt with in chapters. First, it may be easy to theorize that the system should be sensitiv environmental structures, but it places the onus on the model to enumerate and to contain mechanisms which provide the necessary sensitivity. Second enough merely to propose that the functional constraints imposed by a real i are important; the relative constraints must also be found. Third, arguing tl representations are a more natural way of storing and learning about tempo does not address the difficult problem of developing mechanisms to encode relationships. Finally, there is the issue of how prior knowledge will impact

The TRACE model addresses all of these issues directly. Learning in TR comes as the result of correlated neural activity; factors which influence sucl therefore, will necessarily impact learning. This provides the human cogniti with the sensitivity required by the learning system. In such a system the ef such as arousal on learning can be understood in terms of the modulation of

Further, such a learning model provides a natural explanation for consolidat period of consolidation corresponding to the length of time a cell assembly is of the important challenges in this dissertation, dealt with most directly in Cl be to show that the mechanisms of the TRACE model are capable of dealing w various kinds of interventions which impact learning found in the consolidat These interventions, which include arousal, are important in building a fram which the sensitivities can be understood. The basis of this framework is tha sensitivities are not limited to sensory information, such as being aroused by snake, but include cognitive states such as clarity and confusion, and learned such as discovering that certain action lead to rewards. Further, the reminisc prove crucial in showing that the functional constraints found in TRACE, par neural fatigue, are necessary since they are critical to simulating experiments been successfully modelled in more than 30 years since their original publica these mechanisms in place, it will even be possible to show that reminiscence adaptive consequences.

This dissertation begins with a review of consolidation and related data the reminiscence data. This chapter provides the crucial evidence to support model of learning. The important points in this chapter are that the consolic susceptible to interventions that can positively and negatively affect learning that this susceptibility comes as the result of the correlation between learning Following that will be a chapter which examines consolidation from the persp credit assignment. In this chapter the key issue will be whether a consolidati learning theory is powerful enough to account for the diversity of human lea this groundwork has been laid the TRACE model will be presented in Chapte come a chapter which discusses consolidation within the context of the SESAI architecture. The basis of this chapter will be to show that TRACE is capable learning necessary to account for the consolidation data and to show the gen

consolidation based model. The final major chapter will be devoted to the re
data. Modelling this data requires an extension of the TRACE model called M
which incorporates a large number of cell assemblies in order to model sequ

[1]Much of cognition appears to involve generating sequences even w
world appears to be static. Thought itself, for example, is a sequence of idea
which do not appear to be sequential, such as looking at an object, can be ma
as the eyes look from one facet of the object to the next.

CHAPTER 2

CONSOLIDATION

Introduction: Defining consolidation

One of the difficulties in studying consolidation is that it is not well def Consolidation, as it is generally referred to, is what happens between the tim occurs and when the memory for the event becomes permanent. In this cha will be on the time course of consolidation and the experimental factors whic throughout the rest of the dissertation the focus will tend to be on the proce the physical factors which account for it. Most consolidation studies focus o issues: 1) What is the time course of consolidation? and 2) What is the proc That there is a time course at all might be somewhat surprising in the light o connectionist models in which learning comes in the form of changes of con strength between neurons; such changes could easily occur in a fraction of a of the difficulty of determining the time course of consolidation appears to b at least three different events that impact the permanence of memory. Becau events impact memory it is easy to confuse their effects, and the consolidatio sometimes seen as being full of contradictory results. With care, however, a between the three events can be made and a clean study of each is possible. events can be broken into temporal categories ranging from the very short t long term.

The shortest duration event is the one that will be referred to as consol dissertation. The evidence for this type of consolidation comes from a large experiments which show that a number of factors, ranging from psychologic: to electroconvulsive shock, can interfere with the memory for an event, and of interference is directly related to the amount of time between the event an factor. The time course of this type of consolidation is on the order of a few physical changes associated with this type of consolidation form the basis of system discussed in subsequent chapters.

The second event which impacts the permanence of learning involves tl process required to make the physical changes whether they come in the for: synaptic efficiency or the coding of RNA sequences. For the remainder of th this will be called *secondary* consolidation. There is evidence to show that this takes substantially longer than what I am calling consolidation, perhaps on t half an hour or longer (for reviews discussing the differences in the two type consolidation see (Landaur, 1964; Miller and Marlin, 1984)). One of the wa distinguishing this event from consolidation involves the types of interferen Whereas simple interference, such as resulting from psychological manipulat possible with consolidation, the longer chemical process is not susceptible to interference, but more substantial interventions are necessary, generally inv the chemical process of the synaptic change.

A third type of event has been labelled as consolidation and involves v periods of time, on the order of years. The evidence for this event comes frc with damage to the hippocampus. It has been found that damage to the hip selectively impairs memories; the more recent the memory the less likely it is retrievable once the hippocampus has been damaged. Very old memories, o hand, can still be retrieved even after such damage. The most popular curre that memories consolidate in the hippocampus and that the process takes ext periods of time. Other explanations are plausible however. It is possible, fo the hippocampus is a kind of interface between an organism's perception of

its memories. In such a scheme damage to the hippocampus would impair th
retrieve memories, but not the memories themselves. The availability of old
be due a kind of bypass mechanism; when a memory has been reactivated e
may no longer require the hippocampus. Such a theory is in accordance wit
on cognitive maps where it has been shown that the hippocampus is central
processing of spatial memories (O'Keefe, 1989; Squire, 1992). Regardless,
the hippocampus is quite specific and not strictly interesting from a credit as
of view because there is no evidence that the "consolidation" process in the h
has any effect on the strength of learning. On the contrary it is well known t
of learning, as measured by the ability to recall, diminishes with time; theref
hippocampus may well play a role in how a memory is retrieved; there is no
believe that it is a factor in the organism's ability to retrieve a memory beyon
retrieval mechanism.

The two longer term events are called consolidation because the right k
interventions during the time course of these events can affect an organism's
a memory. This is also the case for short term consolidation, but the import
lies in the types of interventions possible, which, in this case, include psycho
interventions. This susceptibility to psychological intervention means that th
system itself can impact the strength of learning. The implications of this fac
enormous; it means that the cognitive system does not have to treat events
terms of the prior discussion of credit assignment, this susceptibility provide
for the cognitive system to translate importance into effects on learning.

Such a theory of consolidation is not traditional. Many researchers, in
consolidation theorists view consolidation as a postprocessing event. Becaus
consolidation is generally viewed as fundamentally separate from informatio
and because it is considered a passive "unconscious" operation many researc
learning and memory have not found it to be a useful construct (Weingartne

review this position while arguing against it (1984)). This dissertation will ta opposite position, presenting a model of consolidation based on a radically (perspective. The claim is that consolidation is not separate from processing, consolidation stems directly from processing; as such consolidation is an act which is fundamentally tied to all of the factors which affect processing. Fur shown that consolidation is central to the human learning biases towards coı repetition and importance.

The rest of this chapter will be divided into several sections. In the firs evidence for consolidation will be reviewed. This evidence will show the basi of consolidation and some of the interventions possible. The second section related paradigm called reminiscence. Reminiscence, like consolidation, is nc understood, even to the point where its existence is sometimes questioned. ' reminiscence data is critical because it establishes the linkage between consol importance. One of the ways in which this is done is by presenting a model consolidation which can account for the reminiscence data, data which has n satisfactorily accounted for by any other model. The last section is an overv implications of the model with respect to credit assignment. Later chapters w model and its implications for credit assignment in substantially greater deta

Evidence for consolidation

The goals of this section are to provide an overview of the consolidatioı and to build a case as to what the theoretical constraints are that a consolidat meet. There are several important constraints that will be developed. First, the consolidation process. Second, will be the fact that consolidation is not ı ballistic process, but is an active process that can be affected in positive and according to the cognitive state of the organism. Further, these effects transl into changes in the strength of learning. Finally there are the factors that im consolidation.

Retrograde Amnesia

Most of the consolidation literature concerns the phenomenon of retro amnesia. Retrograde amnesia refers to the loss of a memory due to some po event, usually some type of trauma or shock. The fact that at one time most retrograde amnesia data involved trauma or shock is actually responsible for the confusion involved in defining consolidation since some types of trauma any of the three types of interruptions which have been used to define conso basic premise of the consolidation literature is that if learning were instantar retrograde amnesia could not easily be explained; after all, there would be n trauma could select the recent memory from any other memory. If we grant performance impairment caused by retrograde amnesia is in fact a reflection of the learning process, then retrograde amnesia holds the potential to revea about the time course of consolidation. Performance, or recall, is disrupted occurred in the recent past. By controlling the time between the events to be the disrupting events it should be possible to determine the nature of the lea time. There exists a large body of studies dealing with retrograde amnesia in forms, whether it is induced through electroconvulsive shock (the most com drugs, or head injury. Some of the studies use animal subjects, others, parti examining the effects of head injuries, use human subjects. Due to the natur experiments however, many of them involving physical damage to the brain, studies use animals. The most often used paradigm has been to put a subjec in a one-trial learning experiment and then at a controlled time interval later electroconvulsive shock (ECS) to induce memory disruption.

Electroconvulsive Shock

Chorover and Schiller (1964) presented a typical ECS experiment. In t experiment, rats were tested for their average time taken to step down from a a grid floor. Animals were then matched on the basis of their step-down late and assigned to three experimental groups and two control groups. In the o phase of the experiment when the rats stepped down onto the grid they were shocks. The first group of rats was simply given the foot shocks. The secon subgroups that also received ECSs at intervals of 0.5, 2, 5, 10, or 30 seconds shock depending on the subgroup. The third group only received the ECS. procedure was repeated over three consecutive days and the SDLs for each g recorded. Virtually any learning theory would predict that the rats would le relationship between stepping on the grid and getting a footshock. In fact th what the results showed in the absence of an ECS. Animals that only had foo an average latency time of about 30 seconds. Also of note was that with a 30 between the foot shock and the ECS, performance was indistinguishable from rats which did not receive an ECS. At a delay of 30 seconds, therefore, it doe that the ECS interfered with learning. However, as the foot shock to ECS inte decreased, the latency times fell and were especially short in the 0.5 and 2 s Conclusions that could be drawn from this study, based upon the latency tin evidence that learning is complete after about 10 seconds, and that the bulk takes place in 2 to 5 seconds.

The premise that ECS work is built upon appears to be sound, but doul validity of this line of research were raised from its early stages. The most c explanation for retrograde amnesia due to ECS is that ECS disrupts consolida Spevack and Suboski surveyed a number of alternative explanations to conso 1969. All of these were variations on a hypotheses that no process was disru the shock itself became a part of the learning. It was somehow related to the perhaps working as a highly aversive stimulus or working to increase the avo response. For example, a rat might learn to run to the right in a Y-maze to ga reward, but with a huge electric shock soon following it, the shock could pot seen as part of the outcome of running to the right. If the pain outweighed t running to the right would be something to be avoided. A number of studie that argue against these possibilities (Spevack and Suboski, 1969, King, 196 these explanations fell short of providing a more compelling explanation, the possibility that there may be more to retrograde amnesia with respect to ECS determined by a simple analysis. Other problems existed with the literature retrograde amnesia. The time course of consolidation reported varied from seconds (Chorover and Schiller, 1964) to as long as a day or more (Misanin, Lewis, 1968). Chorover and Schiller did point out that different levels of foo lead to different lengths of consolidation, but the variations they describe ar of seconds not hours.

More recently, the doubts about retrograde amnesia have been given n Among the new issues raised are that the overall effects of ECS on the nervou simply are not understood well enough to make any strong claims. ECS coul example, somehow damage the retrieval mechanism needed for certain mem and Malin point out that more recent studies have found that in many cases amnesia is not permanent (Miller and Malin, 1984). This would indicate that damaged is in fact the ability to retrieve the new memories, not the memorie Miller and Malin's studies indicate that consolidation is a relatively quick pro less than five seconds. They go as far as saying that "we believe that this ext of consolidation is one of the few established facts concerning the nature of It is worth pointing out that the five second interval is exactly the gradient p in reviewing classical conditioning experiments (reviewed in (Hilgard and Bo as being the maximum time which can elapse between a response and reinfor the reinforcement to have an effect without depending upon other mechanis

Retrograde Facilitation with Drugs

Retrograde studies using drugs actually fall into two study types: those amnesia caused by the drugs (Parker and Weingartner refer to this as facilita memory), and those that study facilitation of memory caused by the drugs. Weingartner (1984) present a review of a number of these studies and the ef various drugs studied. Experiments using drugs follow the same general par ECS experiments, but often use humans as subjects. Subjects are divided int and control groups and then are given some test material to be learned. Imm this the test groups are administered the drug being tested. Later both grou recall. Some drugs produce enhanced recall and some depress recall. Addit tests have been done with the same drugs where the drugs are administered material is given.

One of the most revealing insights from these experiments is that some produce the opposite effect when given before training than when given afte Alcohol, diazepam (valium), and nitrous oxide, for example, are known to pr amnesia when given before training, but can actually work to facilitate memc after training. It has been hypothesized that this is because consolidation an involve different processes. This explanation appears to be lacking, howeve effects of a drug administered before training would be unlikely to have wor memory is encoded. Other explanations seem reasonable however. The nex concerns the fact that psychological interference can impact the consolidatio drug like alcohol could serve to generally dampen neural activity. Then in th is administered after the training there will be less inhibition, and therefore i from other active processes. If it is administered before the training the activ training will itself be dampened leading to lessened consolidation. Such a th partial accord with Parker and Weingartner's own conjecture which also hyp drugs may stimulate the reward system as well.

As with ECS, there are a number of important questions that have not b answered in regard to the overall effect of drugs on the nervous system. Wh fascinating about these studies, however, is that they raise the possibility tha is not simply a process that is started and then either runs its course or is in the contrary, the drug studies would appear to indicate that consolidation is process. Such evidence would appear to contradict theories that hypothesize consolidation is an analytical process which aims to determine whether or nc worth storing. It is difficult to see how drugs would affect such a process, ar to account for asymmetric effects such as are produced by alcohol.

Further evidence for the theory that consolidation is an active, malleab be found in another class of amnesia studies which indicate that consolidatio affected by cognition itself.

Retrograde Amnesia Due to Interference

At least one study does exist that is not subject to the kinds of problem the retrograde amnesia work done with ECS and drugs (Tulving, 1969). In t amnesia was not induced physically, but through interference from another presented subjects with lists of words to be remembered. Subjects were instı whenever a name of a famous person (such as Christopher Columbus) appea to make sure that they remembered that name. During the recall test they w recall the name first, before going on to the other items from the list. The id task of recalling the famous name would interfere with the task of recalling tl words. The questions to be answered were; if there would be interference at what would the temporal nature of the interference be.

The lists were 15 words long. The high priority names appeared in po
and 14 in the test lists and not at all in the control lists. When the presentat
seconds or 1 second per word, recall of words from input positions 7 and 13
preceding the positions in question) was approximately twice as high in the c
in the high priority lists. In other words when subjects tried to remember th
word it somehow interfered with their ability to remember the word immedia
it. At a presentation rate of 2 seconds per word there was almost no differen
presence of the high priority words did not seem to affect the recall of words
following them. Tulving interpreted these results as evidence of consolidatio
priority words interfering with the ongoing traces of the preceding words. I
only the immediately preceding word was greatly interfered with, meaning th
of the trace would be between 0.5 and 2 seconds. An alternative explanation
rehearsal. If subjects were rehearsing as the test went along, they would swi
rehearsing the high priority word upon its presentation. However, Tulving p
this is unlikely due to the asymmetry of the effects. Subjects would be just a
forgo rehearsing the words after the high priority word.

The Tulving study indicates a kind of negative access to the consolidati
In this case it appears that because attention was shifted away from the conso
memory learning was adversely affected. In and of itself this appears to be a
learning effect; if attention can be equated with interestingness or usefulnes
attention would seem to indicate that the previous focus of attention was unw
learned. This recalls the earlier discussion of complexity which equated proc
worthiness of learning. Other results, however, will show that this is mislead
a difference between a cognitive shift in attention of the type found in the Tu
and an environmentally driven shift in attention as might occur when passin
doorway or mountain pass. Although working out the basis for this distincti
further discussion (the mechanisms are discussed in Chapter 5 and the proc

conclusion), it does appear to give credence to the case that the cognitive sys type of access to the consolidation process. This notion of cognitive access w developed later in this chapter.

Distributed vs. Massed Practice

Another body of work that provides insight into consolidation concern performance in distributed versus massed practice trials. There are two relat involved. Typically both test recall of items in list learning experiments. In the variable to be studied is the length of time between words in the present In the second paradigm a target word is picked and the test condition is the occurrences of the word. In one group, the massed practice group, the word set number of times consecutively within the list. In the other group, the dis practice group, the target word will appear the same number of times in diff through the list. Essentially there are "rest" periods for the target trace betw presentations in the distributed test while in the massed practice test the targ appear the same number of times, but consecutively within the list; there is intent is to test the temporal interactions going on in learning. The second t especially interesting because it appears to get around the interference probl Tulving study. It is doubtful that a word would interfere with itself, so a stri model would predict that performance would be better in the massed practic the distributed practice case. However, given that the time course of learnin longer than the presentation rate, then each word may be still in the learnin it is again presented. Then the new presentation may have little effect. In th practice case, on the other hand, there will be "rest" periods between the pre any given word. This should allow the consolidation process to be relatively the next presentation of the word, and hence the prediction would be that pe would be enhanced.

Hintzman (1969) reported results on experiments on the apparent frec words in massed versus distributed practice. Three experiments were perfor lines described above. Two types of test were used: a paired-comparison tes decision was to choose the more frequent of two alternatives. In the second judgement of the number of appearances was asked for. In the first experim words appeared consecutively 0, 1, 2, 4, 6, and 10 times. In the second anc experiments, the spacing or number of items intervening between two repeti varied. Apparent frequency, as measured, by reported responses, increased This would appear to back up Hintzman's hypothesis that in the trials where presented consecutively, the presentations tend to meld together instead of b separate cases. However, it is important to note, that the analysis is not simp Tulving study indicates, there are a number of factors that need to be carefu For example, in the distributed case the intervening words could actually int traces of the target word as was noted before. The interference model could stretched such that words would interfere with themselves. Such an interpre other problems, however, such as why rehearsal is effective.

Reminiscence

So far the evidence reviewed for consolidation leaves a number of poss explanations available. There is compelling evidence that there is a process l seconds or less which can be affected in both positive and negative ways. Th is similar to the learning theory developed by Hull which hypothesized that l due to a stimulus trace that lasted approximately five seconds and rose and f according to factors such as reward (Hilgard and Bower, 1966). Negative eff come from factors such as electric shocks, drugs, or interference from other events. Thus far the only evidence for positive effects has come in the form drugs which leaves open the question of whether cognitive events can have a influence on consolidation. There is, of course, a large literature on the effe on learning, but such rewards are physically manifested, such as food. This that such instances are not important to the study of consolidation, indeed tl will be addressed later in the dissertation, but they do not address the issue cognitive effects. Fortunately, there is a related body of evidence which not that cognitive events can have a positive impact upon consolidation, but whi provides insight into the issue of the process underlying consolidation. This called reminiscence, also happens to be the source of a great deal of controve learning theorists.

Reminiscence refers to an improvement in recall for an event over time properly, reminiscence denotes improvement in performance of a partially le occurs while the subject is resting. In other words, performance for a traine poor right after the training trial, but it can actually improve after a period o study showing results of this type was done by Bregman (1967).

Another large body of evidence for reminiscence concerns motor learn such as pursuit rotor tests (Eysenck and Frith, 1977). While it is not clear th direct correlation between motor tasks and cognitive tasks, some of the varia have suggested that there are cognitive components that could account for th effect.

The two explanations for reminiscence most often advanced are consol inhibition. Consolidation theorists generally explain reminiscence by the fac immediate performance tests, the consolidation of the training trace has not and therefore performance will be poor. After a period of rest, consolidatior solidifies the memory trace, leading to better performance. Later degradatio performance comes after consolidation ends and normal forgetting sets in. T with this theory is the evidence that consolidation is complete in approximat seconds. The longer time course associated with secondary consolidation is either because it does not explain why there is no performance increase asso low arousal case. Inhibition theory, on the other hand, proposes that durin is a build up of reactive inhibition which negatively affects performance. Du periods, this inhibition has a chance to dissipate, leading to improved perfor However, in a pair of studies concerning the relationship of arousal and lear Kleinsmith and Kaplan (1963; 1964) obtained results which challenged both explanations.

Kleinsmith and Kaplan found that the reminiscence effect was very pro high levels of arousal, and nonexistent at lower levels. It is worth noting tha measured by item rather than by subject; so, for example, one subject woul low levels of arousal within one trial. At high levels of arousal the recall cur essentially a U rather than the traditional inverted U associated with learnin recall is high, but quickly drops off to very low levels. However, after a peri minutes recall actually begins to improve, by as much as 400% in the origina before falling off gradually in the long term due to natural forgetting. The K Kaplan results are difficult to interpret from a consolidation perspective bec time lag involved. If consolidation only takes five seconds then it is complet reminiscence effects begin to appear. The consolidation model on its own al explanation of the low arousal case when recall is high initially. Interference similar difficulty explaining these effects. The difficulty is in determining wh with and why such interference only happens when arousal is high. For the numerous attempts have been made to replicate these experiments with mos the original results (Eysenck, 1977; Weingartner and Parker, 1984; Revelle 1990).

Theoretical Background

A number of theories have been proposed to deal with the evidence for reminiscence. Most use consolidation, others propose alternative mechanism interference, still others claim that the evidence for consolidation is too weak theory on.

Impediments to a Far-Reaching Theory

One such argument, made against consolidation, is made by Keppel (1 Keppel claims that the evidence cited in support of consolidation is "not very particular he reviews some of the literature on reminiscence and arousal and while most of the evidence is supportive, it is not compelling. Keppel claims such as those obtained by Kleinsmith and Kaplan are so dramatic that they s replicated. However, Keppel himself points to studies that strongly support and Kaplan data. The studies which he claim only marginally support the da support it all, use differing test paradigms, such as inducing arousal with wh Arousal induced through noise will have additional and different effects on a arousal stemming from some part of the test itself such as a particular test w itself might serve as a distractor, shifting part of the subject's attention away In general, it would seem that comparisons made between naturally occuring arousal would seem tenuous at best.

Keppel concludes that cognitive theorists will "avoid explanations that human as a passive organism completely at the mercy of involuntary physiol processes." On the contrary, it is the very fact that consolidation and arousa involuntary that makes them powerful. As was argued in the first two chapt learning and learning in new domains must be automatic and not deliberate. consolidation, as it will be developed through the model presented in this di that, in conjunction with arousal and other factors, it affords a different kin one which is flexible and sensitive to a range of architectural considerations.

Keppel does raise some salient issues. The literature does not appear t any one theory. A number of reasonable mechanisms have been proposed, l on their own, each falls short of providing a complete explanation of the dat: together, the task of analyzing the end product becomes difficult due to the i the pieces.

Theoretical Factors

Interference Theory

The leading argument used to explain reminiscence without the use of (is interference (or inhibition) theory. Interference theory posits that the poc due to interference from the original presentation of the word. As the subjec inhibition dissipates and performance increases. Peterson (1966), and Parke Weingartner (1984) review some of the problems that inhibition theory cann its own. However, both propose models that use consolidation in conjunctio of interference.

Inhibition is a well established neurological fact (Milner, 1957). The qu regard to consolidation and reminiscence, is whether inhibition on the molec neuronal level, shows up at the molar level; the behavioral level. A number c memory priming studies have been done to show just such effects. Neely pr such study which shows an inhibitory effect at the molar level (Neely, 1977) involved was a word-nonword classification task. Prior to each visually prese string a priming string was presented. Subjects could expect certain relation priming word and the target if the target were a word. For example, if the pı were BIRD they could expect the target to be the name of a type of bird, this no shift trial, because the prime was expected to be related and attention wou be shifted. In the shift case, if the priming word were BUILDING the subject a part of the body to be the target word. The control condition was a primin XXXX in which case the subject could expect a bird, or a body part, or a builc equally often. The subjects were then tested on their reaction times for diffe combinations of expectations and shifts. The results showed both priming a effects when compared against the control conditions. Inhibition was most p trials where there was a shift to a totally unexpected word that was unrelated word.

The evidence for inhibition, and studies such as Neely's and the Tulvin discussed earlier show that any complete model of learning must account for effects. It is still far from clear, however, how interference alone can be usec for the reminiscence data.

Two Stages of Memory

Many information processing models include more than one stage of m typical model would include some short term memory store as well as long te The evidence for at least two stages of memory is compelling (Miller and Mar a number of other models (Peterson, 1966; Neely, 1977) have included two mechanisms. Miller and Marlin call their two memory systems passive and a These would correspond roughly to long term and short term memory. They establishment of passive storage is a consequence of its representation in act What most of the models with two stages have in common is a relatively tran powerful system for short term learning, and a weaker, yet more permanent long term learning.

The two stage model is appealing because it can easily account for half Kleinsmith and Kaplan paradigm. In the low arousal case short term perforn because the items are in the first stage of memory when retrieval is easy. Ho model cannot by itself account for reminiscence; the problem is how such a account for the fact that in the high arousal case there appears to be no shor Indeed one of the reasons that the reminiscence data has come under fire is e it appears to directly contradict the standard memory model which has long memory.

Fatigue

A neurological concept that is less readily accepted is fatigue. The reluc accept the fatigue construct comes as the result of experiments that involved stimulating neurons. Since such neurons can keep firing indefinitely it has g presumed that they do not fatigue. Such data are not pertinent to the fatigu however, because these experiments have not typically measured the output stimulated neurons. Even a heavily fatigued muscle, for example, will still ha to contract; where fatigue shows up is in the muscle's diminished capacity to Atwood, experimenting on crustaceans, has found in numerous cases (review (Atwood and Nguyen, 1990)) that responses of a neuron are "markedly redu chronic stimulation. While these data cannot be directly extrapolated to hun support the general theory.

At the neuronal level the firing of neurons is a physical activity. Like a physical activity this one requires at least one energy source. In the case of n are actually a number of materials necessary for producing firing, most impo being transmitter substances. Fatigue would presumably come when the con some or all of those materials as a result of the neuron's firing exceeds their rate. As in the case of a muscle, such neurons might continue to fire when st would have a diminished capacity to stimulate other neurons.

In terms of the Kleinsmith paradigm some of the best neurophsyiologic comes from Artola and Singer (1993) who point to experiments which result "depression of synaptic transmission" which has a time course of 5-20 minut interval that would be expected given the Kleinsmith paradigm data. Ito (19 reviews evidence of posttetanic depression in which "repeated activation of a to an enduring decrease of strength somewhat like fatigue."

Much of the early research on fatigue was done at the turn of the centu Kraepelin and his students. There are also modern studies that definitely sh effects. Pomerantz, Kaplan and Kaplan (1969) found that in presenting subj repeated flashes of a single letter each presentation had a positive effect on t ability to recognize the letter up to a certain point. At that point, performanc off as might be predicted, but instead started to decline. This was interprete result of satiation and fatigue at the neural level.

Similar effects of fatigue can be found in perceptual data. One such ph known as the "tilt aftereffect." When stimulated intensely for a period of tim visual cortex suffer a temporary reduction in responsiveness. For example, i stare at a pattern of bars tilted slightly counter-clockwise for a period of time looked at a pattern of bars that were vertical, the vertical bars would appear slightly clockwise. This effect has been tied to fatigue in the cortical cells (Se 1985). These results are sometimes received skeptically because they can als by receptor fatigue which is different than neural fatigue. The Necker cube, while visual is a 3-dimensional effect and therefore probably does not directl receptors, can be similarly explained using fatigue. The basis of this explana hypothesis that the two possible interpretations of the Necker cube inhibit ea any given time one interpretations dominates the other and inhibits it, but ev fatigues and the other will begin to dominate.

The analysis of fatigue provides an excellent example of the difficulty o cognition purely at the neural level. The amount of provable knowledge at tl extremely limited. Models built out of only what is known would necessarily incomplete. On the other hand simply speculating that something like fatigu dangerous. Hebb faced this very dilemma when he first presented his cell as theory. Hebb knew that his model needed certain factors, in particular inhib it work, but because there was no provable evidence for these factors he deci them out of his model. The problem with such a decision is that an incomple have glaring weaknesses. In the case of the cell assembly model this was sho dramatically in simulations done by Rochester, et al. (1956). These simulati cited to this day as evidence for why cell assemblies are not plausible. This i unfortunate because the same paper shows that the cell assembly construct i the addition of an inhibitory factor. Had Hebb included inhibition in his orig cell assembly concept might be much more prominent in the literature and it be given closer scrutiny. The issue for cognitive theorists is how to decide w factors can be plausibly hypothesized. One of the major thrusts of this disse the necessity of the fatigue construct. Because neural fatigue is still not gene by neuroscientists the basis for including fatigue will necessarily be theoretic Throughout this dissertation I will return to the fatigue concept to show how providing clean explanations for data that is otherwise difficult to explain. T example of why a model that bridges the neural and behavioral levels is pote useful, because in the absence of good evidence at one level, the other level r the additional constraints necessary to complete a model.

The first piece of evidence that makes the neuronal fatigue construct at way it can be used to explain the reminiscence data. The difficulty of the ren lies in the asymmetry of the effects; high arousal appears to strengthen learn the long term. If high arousal always lead to improved recall performance v arousal than it would be simple to create a model that directly links learning The low arousal effects are easily explained because they fit the predictions t models would make. The central piece of a reminiscence theory, therefore, r explanation of why short-term recall is poor when arousal is high. Further, must do so in such a way that short-term recall will still be high when arous

To build such a theory a reasonable starting point is to examine the eff arousal on the cognitive system. The major effect appears to be that neural a becomes more intense and concentrated (Oades, 1985). One conclusion that drawn, therefore, is that learning strength is related to the intensity of activi might speculate that something about the intense activity leads to a situation term recall is poor. Fatigue provides a simple explanation as to why this mig The neurons in the areas of intense activity will naturally expend large amou resources and therefore become abnormally fatigued. Since these cells are fa will be less sensitive to reactivation until the fatigue dissipates, and therefore information that they code will be temporarily inaccessible. When arousal is other hand, activity will be less intense and not as much fatigue will build u case the information coded will be easily retrieved because of short-term me considerations.

Putting the Data Together

The number of factors involved in reminiscence seems rather imposing experiments that completely isolate the various components is difficult at be Unfortunately, in the bulk of the literature little heed is paid to the interactio components. Interference theorists, for example, may not acknowledge a fat component and therefore would design their experiments concentrating pure interference. (Actually, fatigue can be viewed as a form of self inhibition, or inhibition as it is usually called.) Even aside from the three mechanisms alre there are still others. As discussed earlier, the reminiscence data points to a1 Most models take at least one of these components as a major tenet and coml some notion of consolidation. The results have been mixed.

The contribution of the TRACE model

Consolidation and Reminiscence

One model does exist which purports to account for all of the consolida reminiscence data - it is the TRACE (Tracing Recurrent Activity in Cognitive El model (Kaplan, et al., 1991). The TRACE model is actually quite similar to th explanation originally put forth by Kleinsmith and Kaplan for the reminiscen explanation relied on the fact that events are represented in the brain by neu Under conditions of high arousal such circuits would become highly fatigued would be difficult to reactivate thereby causing poor short term performance under conditions of low arousal there would be little fatigue and, due to shor effects, performance would be good. The neural circuits referred to by Klein Kaplan are called cell assemblies in the TRACE model as TRACE is an updated Hebb's cell assembly theory.

The assumption that cell assembly theory is built upon is that a given t corresponds to a particular firing pattern in a collection of neurons. These r because they are strongly connected to each other, tend to form a unit; whe of them become active they all become active. The activation of such a unit c whatever that unit, or cell assembly, represents being perceived. TRACE mo dynamics of an active cell assembly.

In TRACE, learning is based upon a variation of the rule that Hebb pro his own cell assembly model (1949).

> Whenever an axon of cell A is near enough to excite a cell B and repeate or persistently takes part in firing it, some growth process or metabolic

> change takes place in one or both cells such that A's efficiency, as one the cell's firing B is increased. (p. 62)

The result of this learning rule is a direct correlation between the activi assembly and learning. As long as the cell assembly is active there will be Xs therefore learning will be taking place. Therefore in the TRACE model the tir consolidation is exactly the same as the time course of activity of the cell asse time course can be interrupted, therefore interfering with learning, and it ca therefore enhancing learning.

The TRACE model also incorporates all of the theoretical factors that ap important in modelling consolidation and reminiscence effects. TRACE (or m SESAME, the cognitive architecture of which TRACE is a part) includes severa inhibition, a mechanism for short term memory, and fatigue. All of these me theoretically derived in TRACE and each has predictable effects on the time c activity of the cell assembly modelled in TRACE. Fatigue, for example, is requ cell assembly model in order to ensure that a cell assembly does not remain a indefinitely. Short-term memory, on the other hand is one side-effect of sho connection strength, a factor in the TRACE model which functions both to pr term memory and also to provide cell assemblies with a temporary boost tha to become strong enough that the cell assembly can sustain itself through rev Inhibition comes in several forms and can serve to shut off cell assemblies ur such as perceptual competition and attentional shifts. While it would be wro completely separate any of these factors from learning, the derivation of how activity in TRACE does not rely upon any of the evidence reviewed in this dis (though some of this evidence is used as support). Fatigue, for example, is r mechanism needed because of the reminiscence data, but rather has a theore role in the time course of activity; that it provides an explanation for reminis lends further credence to its existence.

On the other hand, the original TRACE model did not include arousal. for this is that arousal does not have a general, predictable, role in the time c activity of a cell assembly. A cell assembly will behave in different ways base whether arousal is high or low. TRACE models the generalized - *ideal* - case. arousal, unlike fatigue, is a well documented physiological construct so altho be necessary to include arousal when modeling the general case of the time c activity, it is necessary to include it when modeling particular domains, such reminiscence data.

CHAPTER 3

CREDIT ASSIGNMENT

Given the hypothesized relationship between consolidation and learnir model of human credit assignment can be abstracted. In its simplest form su would posit that the representation for a given event consolidates for up to f During this time associative linkages can be made to the representations of ot consolidating events. The strengths of these linkages are determined by the overlap of the consolidation periods of the representations. For example, an be more strongly linked to another event which followed one second later th followed three seconds later because the consolidation periods have more ov one second time interval. Further, this five second time interval can be impa such as attention, arousal and context . In this way the five second interval a general heuristic which can be flexibly adjusted according to the situation.

The question remains, however, as to whether this five second period i enough to account for the power and diversity characteristic of human learn the emphasis in consolidation research has been on determining the nature c consolidation is, little attention has been given to how consolidation fits into framework of learning. Fortunately there has been work in the machine lear community which indicates that a consolidation-style model is potentially qu its ability to learn. In particular, Sutton (1988) has studied similar issues. H which address these issue *temporal difference* models and the basis for the relativ of a temporal difference model is directly related to the length of the tempora uses. To understand this work is it helpful to examine the role of time in cre

Credit assignment and time

Time adds a great deal of uncertainty to the credit assignment problem number of reasons for this. First, since the effect of an action is not necessai the length of time between the action and when its effects are finished canno without a model of the action. These delays make it impossible to know whic responsible for which outcome when there are intermediate actions before th consequence of an action. The intermediate actions add further uncertainty too may impact the consequence of a previous action. Without a domain the such issues out there is no way to equate actions and outcomes with certaint domain theory presupposes knowledge, in the general case when a domain t available, time would appear to make the credit assignment problem intracta

Fortunately, however, the real world is not quite the general case and c heuristics, while not providing a "solution" to the credit assignment problem effective methods for building domain knowledge. These heuristics could be a kind of domain theory of the world as a whole.

The starting point for such heuristics is determining what a reasonable interval might be between actions and consequences. A simple heuristic wou assume that actions do have immediate consequences. Such a heuristic coulc *contiguity* rule, because it assumes that things that are next to each other (in tii related. Indeed it is the case that some type of contiguity rule is a part of nea learning theory. At the other end of the temporal spectrum would be a heur extremely long time intervals. In a domain such as a chess game, for exampl system using this type of heuristic would wait until the end of the game befo credit to individual moves; by contrast a contiguity-based system would assi move to move. The advantage of using long intervals is that it virtually assu consequences of an action will be finished before credit is assigned. On the c problem of intervening actions becomes very large. In chess an individual m perfect for the situation in which it occurred, but the game may be lost anyw long interval scheme, that move would be assigned blame equally with all of moves even though it might have been the best move in the game. On the ot the course of time good moves should participate in wins more often than pc vice versa. Short intervals, by contrast, avoid the intervening action probler easily handle actions with delayed consequences. Short intervals also requir storage since only a few things at a time are linked. Of course intermediate l are also possible.

Temporal difference analysis

In Sutton's analysis (1988), a generic temporal difference system make prediction and then at a specified time interval later updates that prediction new state of the world. It then will update the mechanism used to make the prediction based upon the new information. In chess, for example, the pred whether or not the current position will lead to a win, or what the best move is. Several moves later the system makes a new estimate and updates the eva function responsible for the original prediction, the idea being that the later should be more accurate. Examples of temporal difference systems include S checkers playing system, Holland's Bucket Brigade algorithm, and Sutton's c Heuristic Critic. Sutton's work examines the issue of the temporal interval s detail. Sutton calls systems that use a maximum interval size *supervised,* imply waiting for final outcomes these systems are effectively getting perfect inforn from a teacher. This may be possible in games, but it is not necessarily poss world situations. What is surprising, especially since Sutton only used situat defined outcomes, is that he found that temporal difference systems, particu differences of only a few time steps, clearly outperformed supervised system tasks. Performance, in this case, was measured by how long such a system t converge to an optimal solution. Another researcher, Tesauro, interested in backgammon and skeptical of Sutton's results, applied a simple temporal dif to backgammon. Tesauro's system, which used very simple board represent started out with no knowledge whatsoever, was able to learn to the point wh judged it superior to every machine backgammon system, including systems trained on massive human expert data sets (Tesauro, 1992).

The advantage found in temporal difference systems using shorter time appears to stem from the intervening action problem. Essentially what such build causal sequences. When a chess game is lost, for example, the loss will the most recent few predictions. However, the next time the states where the were made are reached, the negative effects of the loss will propagate further other states (Figure 3.1). Rather than predicting what the end result of a gai start out by predicting the state of the game a move or two later. As learning

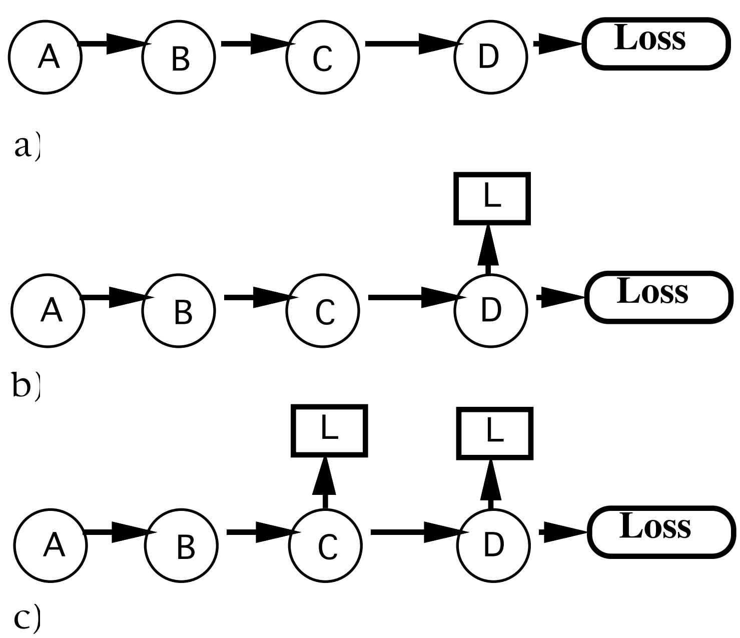

Figure 3.1: In a) the sequence A - B - C - D leads to a loss. In a simple tempo difference scheme at the next occurrence of D the loss will be predicted as in this prediction will then be propagated back to C such that C predicts a loss.

and the predictions become more accurate, then the predictions will begin nc predict the state of the game a few moves later, but also the final state as wel system the individual sequences (of only a few steps), become akin to buildi: When an individual sequence is learned well enough, then it can begin to fur of intermediate goal. For example a particular board position in chess may b win because it will always lead to wins. Further, though it might take longer supervision, short intervals can also effectively capture relationships betweeı outcomes which do take long periods of time because of this building block f (Figure 3.2).

Pure temporal difference analysis does not necessarily apply to the rea the principles remain the same. The first problem with applying temporal di models to the real world is evaluation. Whereas domains such as chess have evaluations, most real situations are not so clear cut. Second, temporal diffe assume that every prediction along the way is for the same event and therefc directly apply to situations where multiple goals are being pursued. Third, s require associating knowledge with specific states, thereby necessitating that track all of the states of the world. Nevertheless, theories of human behavio drive-reduction or pleasure maximization can be cast in temporal difference theories the evaluation functions are pleasure and pain and every prediction to maximize pleasure and reduce pain. Further, temporal difference analysis potential advantages of short time interval heuristics.

While the temporal difference construct is framed purely in terms of m learning, it is quite similar to the analysis of animal learning done by Hull (1 argued for exactly the kind of sequence chaining described here. Further, in evidence for such a theory, Hull concluded that the temporal intervals involv the elements of the chain were extremely short, on the order of a few seconc theory also extended to the kind of backward chaining shown in Figure 3.1,

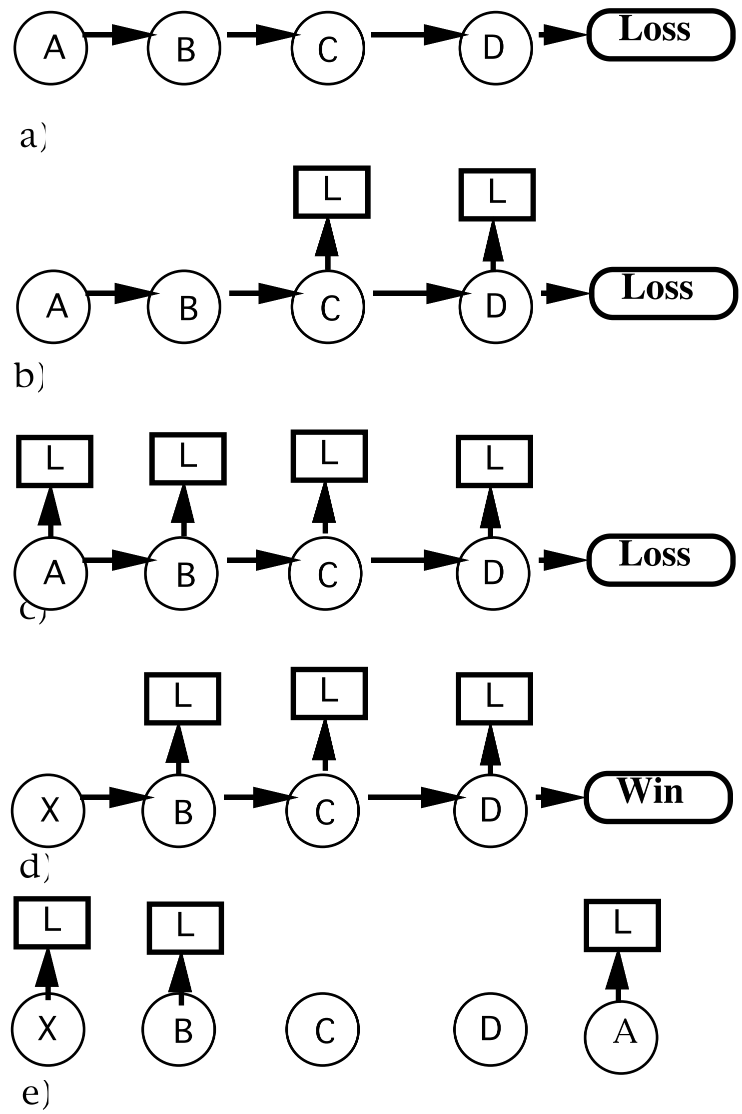

Figure 3.2: In this series of figures state A leads to a loss, though there must intervening moves as shown in a). In b) and c) several occurrences of the se a configuration where A predicts a loss. In d) when B, C, and D are precedec different state they lead to a win. In such a case the predictions of C and D would be updated to reflect that they no longer necessarily lead to a loss. Tl e) which just shows the predictions made at each state. Note, however, that a loss because it leads to states which had previously predicted a loss.

used the more formal psychological term *secondary reinforcement*. As an example secondary reinforcement, Hull used the original experiments which were car Pavlov's lab. In this experiment dogs were presented with the ticking of a m approximately a minute and then a few seconds later the dog would be giver

Eventually the dogs would learn to salivate at the sound of the metronome; a calls an ordinary "first-order" conditioned reflex. Next the dog would be pre black square and then shortly thereafter the sound of the metronome again. of presentations the dog will begin to salivate at the sight of the black square is an example of a "higher-order" conditioned reflex.

In terms of timing from a credit assignment perspective, therefore, it w that relatively short time intervals are superior for learning. Further, in revi on conditioning, Hull (1943) has concluded that animals also build sequence time intervals, later determined to be on the order of five seconds (Hilgard a 1966). All of these factors lend further credence to the supposition that con provide a powerful basis for learning.

Human credit assignment

Factoring the needs of a biological organism into the credit assignment adds a number of constraints to the credit assignment question. These need biased humans away from a rigid approach, but toward a more flexible learn sensitive to factors such as importance and recency. These biases in learning interpreted as being flaws (Nisbett and Ross, 1980; Allman, 1985), because departures from pure rationality, but when viewed from an adaptive perspec to be reasonable adaptations to the difficulties of survival. Combining them draw a general portrait of human credit assignment.

The basis for human credit assignment appears to lie in learning seque learning rule for learning sequence is based upon *contiguity*; linkages are made things that are experienced close together in time. Aside from the apparent t advantages of such a system, there is psychological evidence that humans lea fashion (Hull, 1943; Hilgard and Bower, 1966) as well as the evidence provi consolidation data. The learned sequential relationships are not simple, how weighted by a number of factors relating to adaptive issues such as safety. A are *repetition*, a factor which emphasizes the familiar over the novel, and *importa* factor which presupposes that the organism is capable of differentiating the r of importance in certain key situations and which appears to be related to ar

Contiguity, repetition and importance will be emphasized throughout t dissertation, both at the molecular, the level of neurons, and the molar, the l behavior, levels. The next chapter presents a model which not only accounts consolidation, but which also specifies the role of contiguity and repetition at level; in this case consolidation is the molecular repetition of a contiguity lea significant portion of the dissertation will be devoted to showing that the lea gains a great deal of its power by its ability to vary the amount of repetition which automatically impacts the strength of learning.

Aside from specifying the model in detail, later chapters will deal with l human cognitive architecture as a whole can automatically detect importance a learning system which implements a domain independent credit assignmen affording the cognitive system enormous flexibility in learning.

CHAPTER 4

THE TRACE MODEL

The data reviewed in the previous chapter defines the basic parameters model of consolidation must achieve. As was argued in that chapter, human is surely more than a simple ballistic process which results in the same learn regardless of the situation. Aside from defining TRACE, the basic model usec for consolidation, this chapter will spend significant space on some of the va which the cognitive system interacts with the consolidation process. At time difficult because the TRACE model attempts to isolate one small portion of th system. For this reason some issues will be left unresolved until a later chap more complete model will be presented.

TRACE is not a new model. It was developed in the late 1960s, but was formally presented until recently (Kaplan et al., 1991). However, TRACE, as presented, is not theoretically complete enough to address all of the consolid lack of arousal in the model being one notable example. This chapter will inc presentation of the basic TRACE model and a discussion of some of the mode shortcomings with regard to consolidation. The next chapter will be devoted the model in detail and updating it in order account for the consolidation da

Model properties

TRACE is an updated version of Hebb's cell assembly construct (1949). assembly is a highly interconnected group of neurons that form a reverberat which can sustain activity. Storing information in memory is achieved by st the appropriate cell assemblies; retrieval from memory is the reactivation of assemblies. Cell assemblies serve as the basic unit, or building block, of thou system based upon cell assemblies, thought is directly related to the activity assemblies. Kaplan et al. define four roles of activity for cell assemblies (19 *Activation and perception*. In the TRACE model perception occurs when an enviror event leads to a high level of activity in a corresponding cell assembly. 2) *Pe and dominance*. Connectionist models tend to view perception as a competitive Those potential percepts receiving the greatest support are presumed most li alternative interpretations of the same stimulus configuration. This same cor process presumably applies to thought as well. 3) *Activation and primary memory*. (1892) described primary memory as memory whose retrieval requires no ef memory immediately follows perception. 4) *Activation and consolidation*. Activity the mechanism of consolidation. The learning rule proposed by Hebb directl activity and consolidation; this dissertation will propose several important n but the essence of the rule will remain intact. Consolidation in the TRACE mo a direct result of the reverberation of the cell assembly. While the fourth rol most obviously related to consolidation the other three will also be referred t the dissertation.

Hebb assumed that long term memory is realized by changes in synapt and that this synaptic strengthening is in turn determined by contiguity and neural activity. Hebb (1949) expressed this assumption in the cell assembly which was discussed in the consolidation chapter. Such a rule directly correl and learning. Consolidation occurs when neurons fire repeatedly; the more fires the more synaptic changes take place. If all neural firings lead to the sa synaptic change then interrupting a cell assembly's activity halfway through consolidation period would lead to a level of learning half as strong as what would be achieved. Given that the consolidation period is thought to be abo

this means that a cell assembly, once activated, will be active for approximate
seconds.

Model specifications

There are a number of difficulties with specifying a cell assembly mode arising from the large number of unknowns at the cellular level. Knowledge properties of neurons is still incomplete enough to make the specification of level a formidable task. The TRACE model represents an intermediate solutic modeling the global dynamic behavior of a cell assembly without specifying t interactions between each of its component neurons. In many respects this i models of population dynamics used by ecologists. The advantage of such a solution is that it affords an opportunity to study cell assembly behavior wit deep a commitment to implementation details. Further, the constraints gene experiments with such a molar level model can serve to guide the constructic network models and can specify quantitative behavior which such models ca duplicate. In many ways this dissertation represents such an effort by furth and defining the range of behaviors appropriate in a cell assembly.

The basis of the TRACE model is a collection of state variables represen factors that influence activity in a cell assembly. These factors are collected t system of simultaneous equations and can be grouped into four primary con domains: *input*, *prior experience*, *competition* and *control*.

Input

An input pulse in this simulation is designated I. Input provides the in for activity, but in a well-learned cell assembly, the strong interconnections a neurons assure the spread of activity after that activity has reached some cri

Experience

The connection strength between elements in a cell assembly reflects th corresponding prior experience of the organism. This latent long-term struc expressed as L in the simulation. Conversely, in a cell assembly that is not w some factor that could substitute, albeit partially and temporarily, for the sta that will come to define the cell assembly is necessary. This hypothetical sho connection strength (STCS) is designated S.

Competition

The importance of inhibition has already been raised several times in tl dissertation. One of the key factors which influences the activity of a cell ass in the form of perceptual competition; presumably a given input will tend to number of cell assemblies and only one will become dominant and therefore This competition is not expressed directly in TRACE, but rather is modelled i activity since the amount of competition is proportional to how active the cel

Control

Since the basis of the cell assembly is positive feedback there needs to l counterbalance to prevent a cell assembly from remaining active indefinitely fatigue, designated F, which has already been introduced in the previous cha addition there is an upper bound on the amount of activity in a cell assembly that it is comprised of a finite number of neurons. The final control on activ stochastic tendency of units to drop out over time.

The TRACE equations

These factors come together in a system of simultaneous difference equ greater detail on how these equations were defined see (Kaplan et al., 1991)) these equations is designated by *P*, in memory of perseveration, a term for p activity. It is important to keep in mind that P (and all other state variables) between 0 and 1 where the value represents the portion of active elements at Conceptually it is possible to separate those factors that contribute to the rise from those that contribute to its fall, such that

$$\Delta P = \Delta P_{rise} - \Delta P_{fall} \qquad (1)$$

The rise is influenced by input, positive feedback, the number of units activate and the sensitivity of a given unit to become active. The sensitivity, is a function of *L*, *S*, and *F*. Combining these factors yields

$$\Delta P_{rise} = (P + I\,(1 - P))\,(1 - P)\,V \qquad (2)$$

The sensitivity represents a gathering together of all of the factors that cell assembly more readily activated. This can be represented by[1]

$$V(t) = \frac{(L + S)(1 - F)}{n} \qquad (3)$$

where *v* is a constant preventing *V* from exceeding unity.

The decline component is composed of two factors, namely competitio Just as the rise component benefits from high *V*, the reverse is true for the fa Drawing these factors together yields

$$\Delta P_{fall} = (P^{\theta_1} + P\,(1 - P)^{\theta_c})\,(1 - V) \qquad (4)$$

$ø_1$ and $ø_c$ represent the tendency of units to drop out and a competitive facto and are constants.

Substituting the rise component ΔPrise and the fall component ΔPfall in (1) yields the complete expression for ΔP, such that

$$\Delta P = (P + I\,(1 - P))\,(1 - P)\,V - (P^{\theta_1} + P\,(1 - P)^{\theta_c})\,(1 - V) \qquad (5)$$

The functions for fatigue ΔF and for short-term connection strength ΔS

$$\Delta F = \phi_g P (1 - F)^2 - \phi_d F \tag{6}$$

$$\Delta S = \sigma_g P (1 - S)^2 - \sigma_d S \tag{7}$$

are essentially similar: they both depend on the activity level *P*; they are bot their maximum value of unity; they both decay gradually and contain consta modify the rates of growth and decline.

The input equation is not designed to model a particular input, but ins prototypic input. The input function

$$I(t) = \begin{cases} \alpha \quad \text{when} \quad 0 < t \leq \delta \\ 0.0 \quad \text{when} \quad t > \delta \end{cases}$$

makes no assumptions about the nature of the input beyond the fact that it h Alpha for some duration Gamma and then ceases.

A typical run of the TRACE model is shown in Figure 4.1. Table 4.1 su the TRACE equations along with the parameter settings used in Figure 1.

Discussion

The TRACE model as originally presented was found to meet the theore constraints which guided its construction. Further, it was found to be robus its parameter settings. However, the consolidation data presented in the pre adds an additional set of constraints. At first glance the TRACE model would adequately account for consolidation because its learning rule in conjunction second activation period specify a system in which an interruption of activity the kind negative impact on learning found in the literature. Further examir shows that TRACE has difficulty with several facets of the consolidation data, with regard to reminiscence. First and foremost is the fact that TRACE has n variable. This is accounted for in the original model by assuming that the ur modeled is functioning under "ideal circumstances." "Ideal circumstances" i means a high level of arousal. The second problem, which is difficult to infe 4.1 is the nature of fatigue and short term connection strength. A hint of the be found in Figure 4.1 by noticing that both STCS and fatigue approach near values in a fraction of a second. This is reasonable for STCS which must buil in order to provide the temporary connections necessary for a weak cell asse active. However, in the case of fatigue it is more difficult to justify. What cu happens is that fatigue quickly builds to a near maximum and then slowly fo level of the cell assembly down at a near steady pace. The result is a system nearly as fatigued after five seconds of activity as it was after a half second. will turn out to be the central stumbling block to modeling the reminiscence TRACE and considerable space will be devoted to it later in the dissertation.

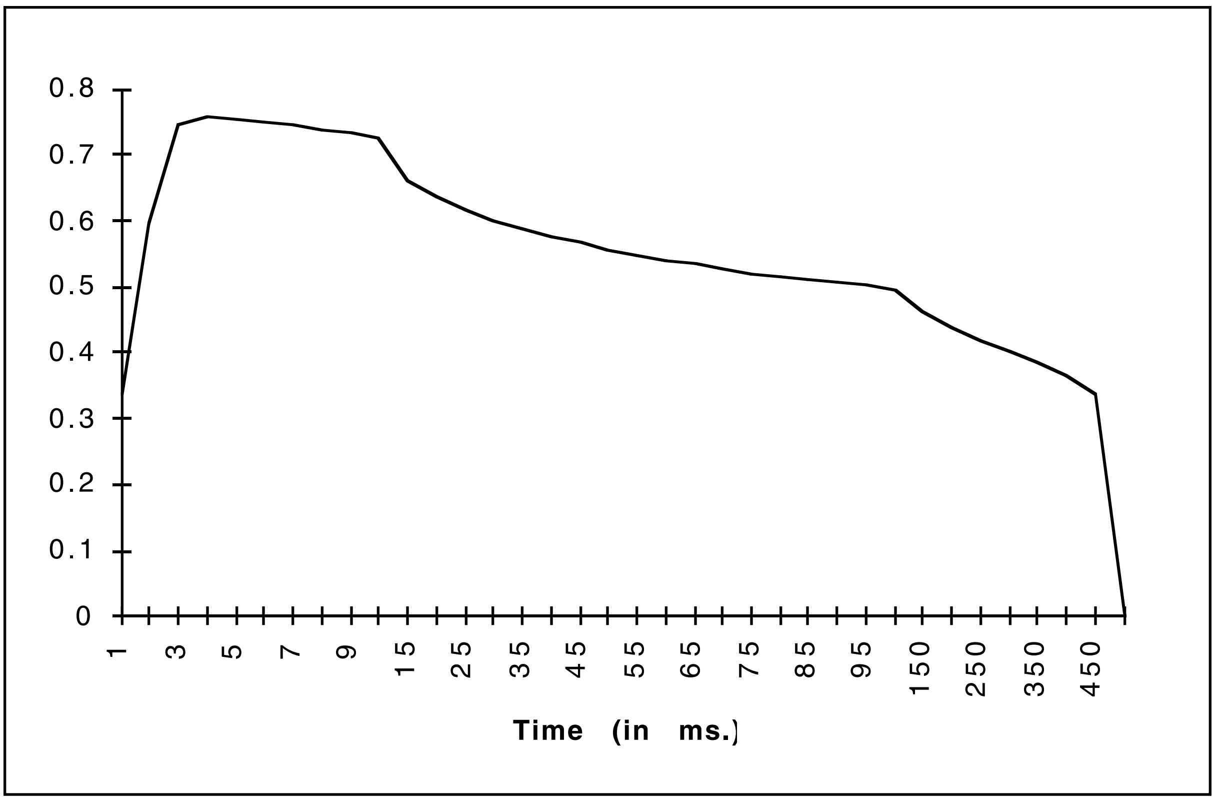

Figure 4.1. The time course of activity in a well learned cell assembly. occurs over the first 10 time steps (100 msec). The time scale is distorted to different phases of activity.

Table 4.1. The TRACE difference equation system as si

$$P(t+1) = P(t) + \Delta P \qquad \Delta P = (P + I)\bar{P}V - (P^{\theta_l} + P\bar{P}^{\theta_c})\bar{V}$$

$$V = \frac{(L + \bar{S})F}{\nu}$$

$$F(t+1) = F(t) + \Delta F \qquad \Delta F = \phi_g P \bar{F}^2 - \phi_d F$$

$$S(t+1) = S(t) + \Delta S \qquad \Delta S = \sigma_g P \bar{S}^2 - \sigma_d S$$

$$L(t+1) = L(t) + \Delta L \qquad \Delta L = 0.0$$

$$I(t) = \begin{cases} \alpha & \text{when } 0 < t \leq \delta \\ 0.0 & \text{when } t > \delta \end{cases}$$

Variable	Interpretation	Initial condition
P(t)	perseverance, activity	$P(0) = 0.01$
F(t)	fatigue	$F(0) = 0.01$
S(t)	short term connection strength	$S(0) = 0.01$
L(t)	long term connection strength	$L(0) = \lambda$
I(t)	external input	$I(0) = 0.0$

Parameter	Interpretation	Unmodified valu
θ_l	unit loss	5
θ_c	inhibitory competition	9
ν	normalization factor	1.5
ϕ_g	fatigue growth	0.14
ϕ_d	fatigue decline	0.0001
σ_g	short term connection strength growth	0.4
σ_d	short term connection strength decline	0.00015
λ	initial long term connection strength	0.5
α	input amplitude	1.0
δ	input duration	10

$\bar{X}$ denotes the quantity (1–X). The state variables P, F, S, and L are ev

the equations for ΔP, ΔF, V, and ΔS; the input variable I is evaluated a

In the next chapter I will examine the TRACE model in detail, paying sp attention to consolidation. The goal of this chapter is to show how systemati modifying TRACE, in accordance with the underlying theory of cognition tha grounded in, can account for all of the consolidation data while retaining the properties and results already achieved. One must be careful when performi undertaking not only to be cognizant of the goals of the modifications, but a of the original simulations. Any modifications which violate the results or ev of the original model should not be made lightly, but must somehow be show necessary and to advance the overall theory as well.

Such a simulation philosophy has always been a principle behind the S architecture of which TRACE is a part. Remember that TRACE itself is an app One of the guiding directions of research in SESAME is based upon the usefu successive approximation where each version of a model is slightly more refi previous version. Rather than building models that are "doomed to succeed" can become arbitrarily complex according to the task domain, the SESAME pl to build models that will inevitably fail because they are as simple as possible building a comprehensive model from scratch is simply too large and difficul successive approximation approach assumes that a more reasonable approac large problems in small pieces. This approach relies upon the effective explo failures that are generated. In this dissertation, for example, I start with a m been constructed to meet a certain set of theoretical constraints. And, while appears capable of accounting for the new constraints outlined in the previo must be modified to do so. For example, arousal was not included in the ori because it was not needed to meet the constraints faced. Therefore this mod inevitably fail when faced with constraints dealing with arousal. However, if sufficiently robust then an additional factor like arousal should not disrupt t

already attained. Further, the addition of arousal is not simply an ad hoc so
in the model, but it arises from a strong grounding in theory.

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[1]In the remainder of the exposition I replace the functional notatic the simpler notation X. It should be understood that a variable X which app hand side of an equation is evaluated at time t.

CHAPTER 5

TRACE AND CONSOLIDATION

The consolidation data reviewed in Chapter 2 focused upon the factors positive and negative effects on the consolidation process. This chapter will mechanisms underlying these effects with the major theoretical division bein those mechanisms which have a positive effect and those which have a negat addition there is a section on the special case of input.

Positive factors

In connectionist systems there is generally one source of positive influe unit's ability to fire: connections from other units. It is tempting to include second factor, but, on the one hand input can be seen as coming from other the other, as we shall see, input as a general category does not always have a on a unit's ability to fire. This is mainly due to perceptual competition; an i will always have a positive impact on a unit, but many times input will be acc inhibition from other cell assemblies stimulated by the input. Direct stimulat only factor which can have a positive effect on consolidation; the SESAME ar also contains control mechanisms which alter the sensitivity of units. Arousa example of such a factor; although it will not directly cause a unit to fire, it w impact upon the likelihood of firing and on the firing rate.

Long-term connection strength

Long-term connection strength (LTCS) is a measure of the ability of one facilitate the firing of another. Within the TRACE model high LTCS correspor assembly that is well learned and low LTCS corresponds to a loosely formed c LTCS, therefore, is a measure of experience. Since higher LTCS brings an inc ability for neurons within the cell assembly to fire each other, higher LTCS sh an increase in consolidation. However, the analysis is complicated by the fac higher rate of reverberation will also lead to more intense fatigue. The increa of fatigue might lead to a kind of canceling effect, nullifying the increased co strength. The empirical evidence does not appear to strongly favor either pc This issue will be examined in more detail later in the dissertation after fatigu carefully discussed. For now the assumption will be in accordance with Heb hypothesized that the increase in structure associated with learning (and her LTCS), will lead to enhanced reverberation.

Simulation runs with different levels of LTCS show the effect of the con activity and consolidation within the TRACE model (Table 5.1). The table sh performance of the TRACE model with different LTCS parameter settings rang 0.2, which is considered to be approximately what the connection strength o assembly will be, to 0.5, which corresponds to a well learned assembly. The with respect to learning are the Consolidation column which shows how long assembly will consolidate in tens of milliseconds and the Peak column which indication of the intensity of activity. In learning terms a well learned cell as consolidate approximately 50 per cent longer than a new cell assembly and s higher as well, the consolidation period will be more productive.

Table 5.1. Effects of long-term connection strength parameter cl

Parameter	Peak	Perception	Consolidation
Long-term connection strength			
0.2	.700	38	295
0.3	.720	40	330
0.4	.741	47	373
0.5	.759	52	427

The leftmost column gives the value of LTCS. The Peak column shows the pe activation during perception. The Perception column shows the length of the period. The Consolidation column shows the length of the consolidation per are in tens of milliseconds.

Short term connection strength

Perception is a competitive process. Because most objects share feature least a few other objects, a given input configuration is likely to stimulate a re number of cell assemblies to varying degrees. Considerable space in this cha devoted to the nature of the competitive process which results in the activati percept out of the large number initially stimulated. This percept is determi such as the degree of match to the input and the internal connection strengt stimulated cell assemblies. The competitive advantage that cell assemblies wi have over those that have over those with low LTCS is pronounced because t reverberatory mechanism, which allows one to perceive a whole object when partial input, is mediated by LTCS. Higher LTCS facilitates reverberation, ma assembly more sensitive to activation. Conceptually, a cell assembly is a kind if an input is a close enough match it is taken to be an example of the object t assembly represents. The potential drawback of such an arrangement is that can easily be mistaken for well learned ones. This is due to the fact that a po be enough to start reverberation in a cell assembly with high LTCS, whereas a assembly which is a particularly good match for the input, but which has lov not be able to sustain reverberation because of its relative lack of structure. to recognize new inputs is critical, some factor is necessary to compensate fo LTCS within a cell assembly. In TRACE it is STCS which provides a temporary in connection strength amongst the neurons in a cell assembly. One side eff which is critical with regard to reminiscence, is that this increase lasts for ab providing one type of short term memory. The functionality of STCS, theref providing a temporary boost to weak cell assemblies and providing for a kin memory.

The major effect of STCS on consolidation, therefore, should be to prov necessary temporary connection strength to allow consolidation to happen. poorly learned cell assemblies may lack the internal structure necessary for r Beyond that, however, STCS need not impact consolidation to any significant

STCS appears to come as the result of a process known as post tetanic p (PTP). PTP is a relatively simple effect, the essence of which is that neurons recently fired will be temporarily more likely to do so again (Ito, 1992; Artol 1993). From a functional point of view STCS must quickly reach a peak level provide enough of a boost for weak cell assemblies to compete with stronger means that any cell assembly that achieves a perceptual level of activation sh near maximal level of STCS.

Like LTCS, STCS is already a part of the TRACE model. Also like LTCS, S has already been shown to meet the necessary constraints including its negli upon consolidation as shown in Table 5.2. STCS plays considerably differen depending upon how well learned the cell assembly is. When the circuit is n STCS is critical in providing the support to generate enough activity for perc therefore consolidation. However, once the level of STCS is great enough to perception, further changes in STCS have a minor impact upon consolidatio cases STCS's role in consolidation is that of an enabling mechanism. In well assemblies, on the other hand, the role of STCS is further diminished as no S required for perception or consolidation.

Table 5.2. Effects of STCS parameter changes.

Parameter	Peak	Perception	Memory
	Low long-term connection strength (l = 0.2)		
Short term growth, s_g			
0.0	.061	–	–
0.1	.090	–	–
0.2	.131	–	–
0.3	.633	33	295
0.4	.650	36	295
0.5	.660	36	295
0.6	.672	38	295
1.0	.698	40	296
Short term decline, s_d			
0.00005	.650	37	299
0.00007	.650	37	297
0.00009	.650	37	296
0.00015	.650	36	295
0.00017	.650	36	294
0.00020	.650	36	294
0.00050	.650	36	284

The left column identifies the parameter manipulated and the values tested. columns give the values of three dependent variables: the height of the peak curve, the duration of perception, and primary memory as measured by dur steps. (A time step equals 10 msec.) A dash (–) signifies failure to achieve a primary memory phase.

Arousal

One of the claims made in the introduction was that there is no "solutic credit assignment problem but that the architecture can provide a powerful s The most fundamental heuristic, and one which is almost universally include learning is contiguity which serves as the molecular basis of consolidation; t most clearly in the learning rule which posits that the (nearly) simultaneous neurons is the basis of change. At the behavioral level there is also contiguit representations of high-level objects, in this case cell assemblies, that are acti simultaneously will tend to be linked together. Another important heuristic i the neural level it is the repetition of contiguous neural firing that defines co the behavioral level the more times things are experienced, the more likely tl remembered.

By themselves these are powerful heuristics which have been exploited number of learning systems (Grossberg, 1969; 1971; Sutton, 1988); howev possible to imagine how they might be extended. Rather than treating event learning might be differentiated by some measure of importance. Seeing a s example, could be considered more important than seeing a squirrel. The ar imbues the brain with the ability to treat such events differentially by provid mechanism which can impact consolidation, and which in turn relies upon tl ability to recognize importance. However, the ability to recognize importanc to be as difficult as the credit assignment problem itself. Fortunately, to som evolution has provided several solutions to the problem of deciding the impc events. Some of these solutions show up in hardware, such as the dominanc information in the human brain. This dominance makes vision the primary sensory information versus other modalities such as auditory or olfactory. C subtle such as the fact that the visual system is particularly tuned to attend t things. The higher the percentage of important events that an organism can more likely it is to survive. Evolution has provided humans with some gener mechanisms which allow for this type of learning.

The most obvious of our importance detectors are nerve ending which importance in the form of pleasure and pain. Further, with a cognitive syste

the ability to make predictions, pleasure and pain provide a way to extend tl
facility with importance events. In the SESAME framework, the hypothesis is
humans are sensitive to physical pleasure and pain so too are they sensitive t
pleasure and pain. In addition to physical pleasure and pain, we hypothesiz
overall state of the brain can effect learning. Confusion, for example, can sti
pain centers, while clarity can stimulate the pleasure centers. Confusion occ
does not understand the current state of the world. This is can be as danger
for an organism as is being physically harmed. On the other hand, clarity si
one's understanding of the world is in accord with the current state of the w
strongly positive state because it means that any actions taken are likely to ha
consequences and therefore are more likely to be appropriate to the circums

Even though they are not directly sensed as is the case with physical pl
pain, the pleasure and pain resulting from cognitive events need not come as
deliberative processes, but can be automatically detected just as nerve endin
physical pleasure and pain. Further, because learning in SESAME is based up
neural activity, when physical pleasure and pain are felt, associative connect
built to them from the active cell assemblies. Therefore these states can be a
the pleasure or pain they brought. In SESAME, cognitive pleasure and pain e
from directly association of this type, such as the kind of association one mi
after putting one's hand on a hot stove, or depend on pattern recognizers su
or clarity detectors. For example confusion occurs when an organism's mod
is at odds with the state of the world. In such a case the world and the cogni
supporting the activation of different sets of cell assemblies. This leads to a
activity is diffuse across a number of cell assemblies. On the other hand clar
when the organism's model supports the same cell assemblies as the current
world. In such a case, activity will be more focused and intense (Figure 5.1)
confusion, therefore, can be read by detectors sensitive to whether the activi

system is focused or diffuse. This means that confusion detection is automa does not rely upon any domain information whatsoever.

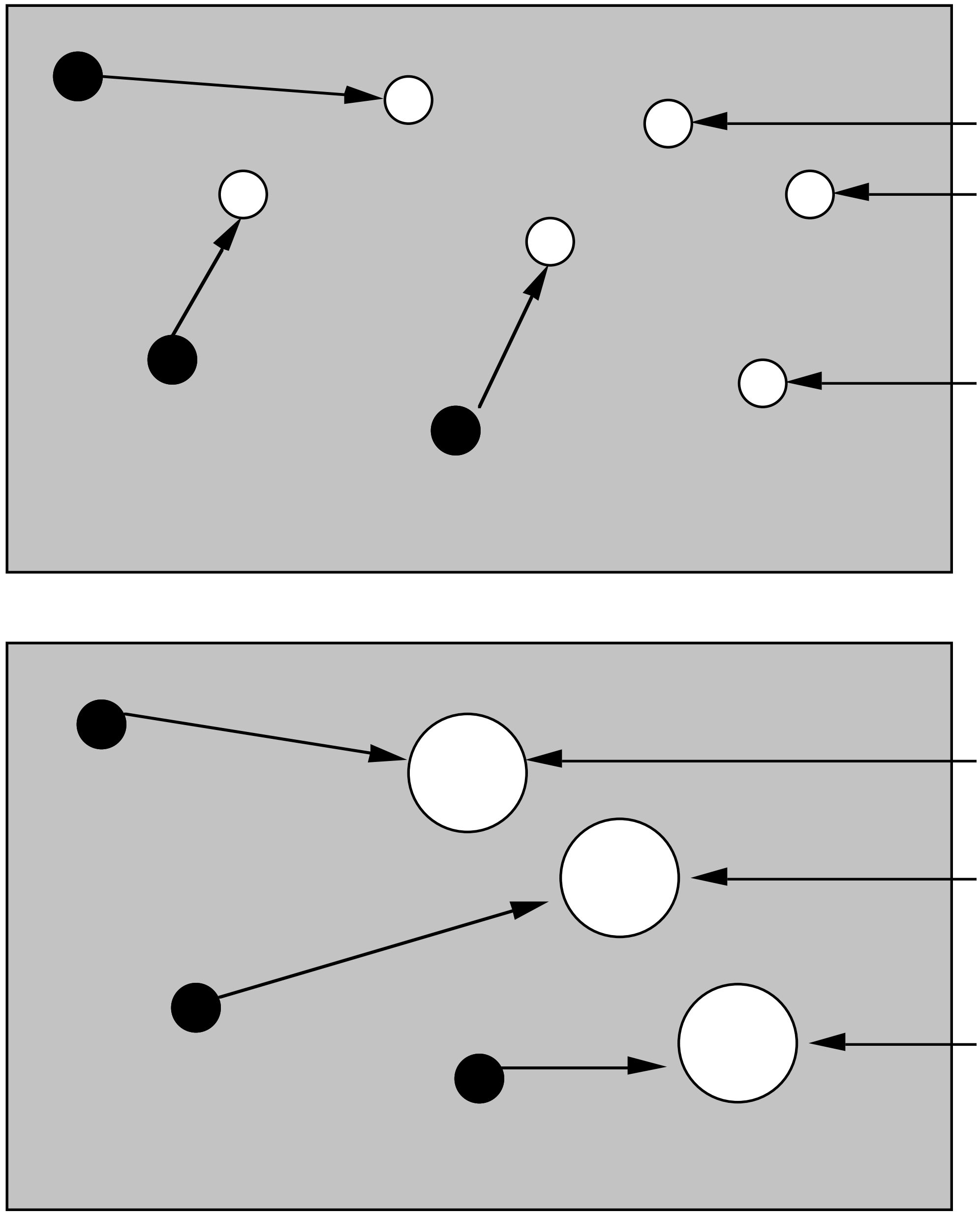

Figure 5.1: Confusion and Clarity. In the figures the circles represent cell as The relative size of the circles indicates their intensity of activation. The larg represent the cell assemblies that were recently active while the white circles cell assemblies that are currently active. Lines from one cell assembly to ano connectivity while lines from outside represent environmental input.

An implication of associative type of learning rule used in this dissertat many elements of a world model, or cognitive map (Kaplan, et al., 1990), ar directly as being positive or negative. A rat which presses a bar to get a rewa to associate the act of pressing the bar with the pleasure it receives from the Further, since the nature of associative structure is essentially sequential anc organisms which exhibit this type of learning should be able to anticipate th which lead to pleasure and pain. This will be discussed in more detail at the chapter, but the principle is similar to Holland's Bucket Brigade algorithm (1 example a rat may learn that when a green light comes on it should press a b reward. In such a case the appearance of the green light is enough for the ra the reward.

Anticipation of positive and negative events is one of the ways in which structure feeds back into the learning system itself. The activation of a cell a strongly associated with pain, for example, will lead to high levels of arousal considering an action that might lead to a state associated with pain, the act may yield an increase in arousal. In this fashion sequences that lead to pleas tend to be learned more quickly than those that do not.

Arousal is the mechanism which translates these evaluations into learn The theory behind such a system is fairly simple. The pleasure and pain cen connected to the arousal system; as pleasure (or pain) increases so does the In turn the increased levels of arousal directly impact consolidation by intens of cell assemblies within the system (one possible architecture which will ach shown in Figure 5.2).

As a mechanism, high levels of arousal should yield an increase in cons whereas lower levels of arousal will result in less consolidation. The SESAME that arousal acts as an activity contrast enhancer. When an "important" ever arousal quickly rises. The timing of changes in arousal is critical since its eff activity of cell assemblies; changing the level of arousal after a cell assembly inactive will have no effect on learning in that assembly. High arousal will le

the activity in some assemblies and suppress other, less active assemblies (n
information theoretic point of view). There is evidence that the arousal syste
accomplish this by flooding the brain with the neurotransmitter dopamine ((
Milner, 1991). Arousal is a new variable within TRACE and therefore represe
change in the model, a change which could be incorporated in a variety of w

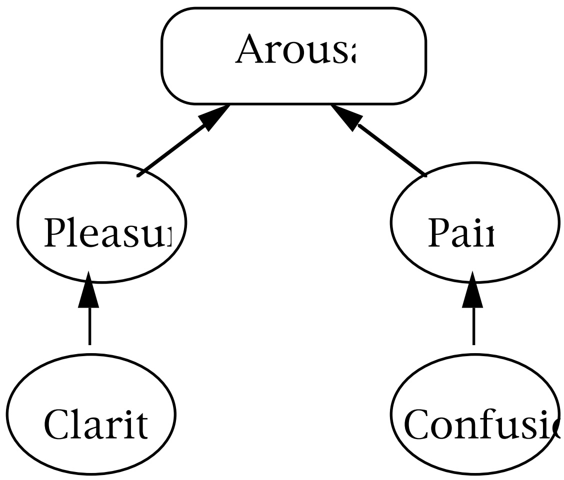

Figure 5.2: Clarity and confusion are detected as shown in Figure 5.1. Each
effect on the pleasure/pain system, which in turn directly impacts arousal.

Experiment 1: simulating arousal

The first step in adding arousal to the TRACE model is to specify the ta
behavior. The major effect of arousal is to increase the strength of learning.
thesis proposes that learning is directly linked to consolidation and that cons
correlated to activity, then arousal must have a direct effect on activity. Incr
could in principle have a positive effect on activity in two different ways, one
the length of time that a cell assembly is active, and two by increasing the int
activity.

In considering whether arousal is likely to affect the intensity or durati
it is useful to consider the function of each in learning. Both provide molecu
repetition of neural firing, but differ in how it is achieved. When activity is i
neurons within a cell assembly fire more often and the high level of repetitio

neurons firing very quickly. On the other hand when the duration is increas
achieved simply because the time period of firing is extended.

The role of duration would appear to be to allow for molar level contig
the firing of neurons within a cell assembly is extended in time it allows the r
the cell assembly to fire contiguously with neurons in other cell assemblies re
events which occurred at other times. For example, in a cell assembly that re
for five seconds, the neurons within the assembly will be active concurrently
neurons of any other cell assemblies that are active within that time period.
primary functions of duration, therefore, is to connect temporally disjoint ev
of the credit assignment discussion the duration is the temporal difference in
Hull termed "the time gradient of the molar trace" (Hull, 1943). This interva
connecting the elements in a sequence; with a five second interval, for exam
extremely difficult to connect two events spaced six seconds apart without so
intermediate transition state. Duration, therefore, is critical to the resolution
of what caused what.

Intensity, on the other hand, is more directly related to the strength of
two cell assemblies are active for exactly the same length of time, the one tha
intensely active will exhibit more learning because of the increase in the firin
neurons. If one is to assume that the strength of learning should be correlat
importance then a reasonable conclusion is that importance yields an increas
intensity.

The scheme proposed in this dissertation is that the two dimensions of
duration and intensity, serve two distinct functions in the credit assignment
main function of duration is connective, allowing disjoint elements of a sequ
associated; intensity, on the other hand, determines how strong the connect
distinctions are not completely clean, since intensity can impact duration and
each addresses a conceptually distinct aspect of the credit assignment questi

To see why this might be a useful approach to credit assignment consic following generic situations. In the first, an organism takes an action. In ma result of the action will not be simultaneous with the action. In such cases it keep the action "in mind" while waiting for the outcome. In a system constru cell assemblies this is done by keeping the representation of the original actic is similar to having an unresolved problem and was an important reason for development of the cell assembly in the first place. In the second situation, l organism's action has had a result. In this case, assuming the representatior action is still active, the remaining problem is how strong the connection bet action and the result should be. This is most simply solved by variations in t activity. One of the important arguments in favor of this alternative is that it potentially undesirable property of duration. Since other cell assemblies will activated during an increased duration, alterations in duration necessarily ir relationship to subsequent active representations. A simple change in intens have such a consequence. Stable durations imply a uniform approach to the which representations should be connected to each other. Since an increase does not necessarily imply a change in duration it seems much more reasona that variations in strength are implemented by varying intensity; it is a safer regard to what connections are made. This can be made clearer with an exar arousal.

An increase in arousal signifies that an important event has just happe of cell assemblies this means that the representation of the event, and perha which lead up to the event, is active. From a credit assignment perspective e is important has happened and the learning system need only adjust the con in accordance with arousal. This is easily done by varying the intensity of ac However, it could also be done by varying the duration of the active represe a strategy has further implications, however, because it impacts the very nex becomes active. If the durations of the active cell assemblies were increased representations would become connected to the newly active cell assembly th the normal case. Conversely, if the durations were shortened, fewer represe be connected to the newly active cell assembly than normal. The basic differ the two approaches can be seen in Figure 5.3 which shows that intensity is a solution to the strength issue than duration.

In the TRACE equations the most obvious place to include arousal is in sensitivity portion of the equation. Sensitivity, after all, reflects the readines to fire. There are two possibilities for how arousal might interact with sensit the relationship could be additive, or compensatory, meaning that an increas quantity can make up for a deficiency in the other. This seems unlikely, hov would mean that under conditions of high arousal a neuron can fire without term connection strength or fatigue. The consequences of such a relationshi assemblies that could remain active indefinitely and cell assemblies that coul activate themselves spontaneously because they would not require an increa connection strength. It is also unlikely because such an arrangement is not s such a case arousal would affect all cell assemblies in virtually the same fashi appears to be a nonspecific mechanism (based upon the neurochemical evide selective results. By making the relationship to sensitivity compensatory the arousal becomes virtually independent of the physical state of the cell assem

The other choice for the relationship between arousal and sensitivity d from such a problem. This choice is that the relationship be multiplicative, c The result of this type of relationship would be that arousal could effectively sensitivity differences between cell assemblies. For example a highly sensitiv assembly (due to an increase in STCS) will have a strongly positive interactio level of arousal whereas a cell assembly that is not sensitive will not. This mu relationship, therefore, serves as a kind of contrast enhancement function w sensitive versus less sensitive cell assemblies. This corresponds to the neuro evidence of arousal's effects (Oades, 1985; Milner, 1991).

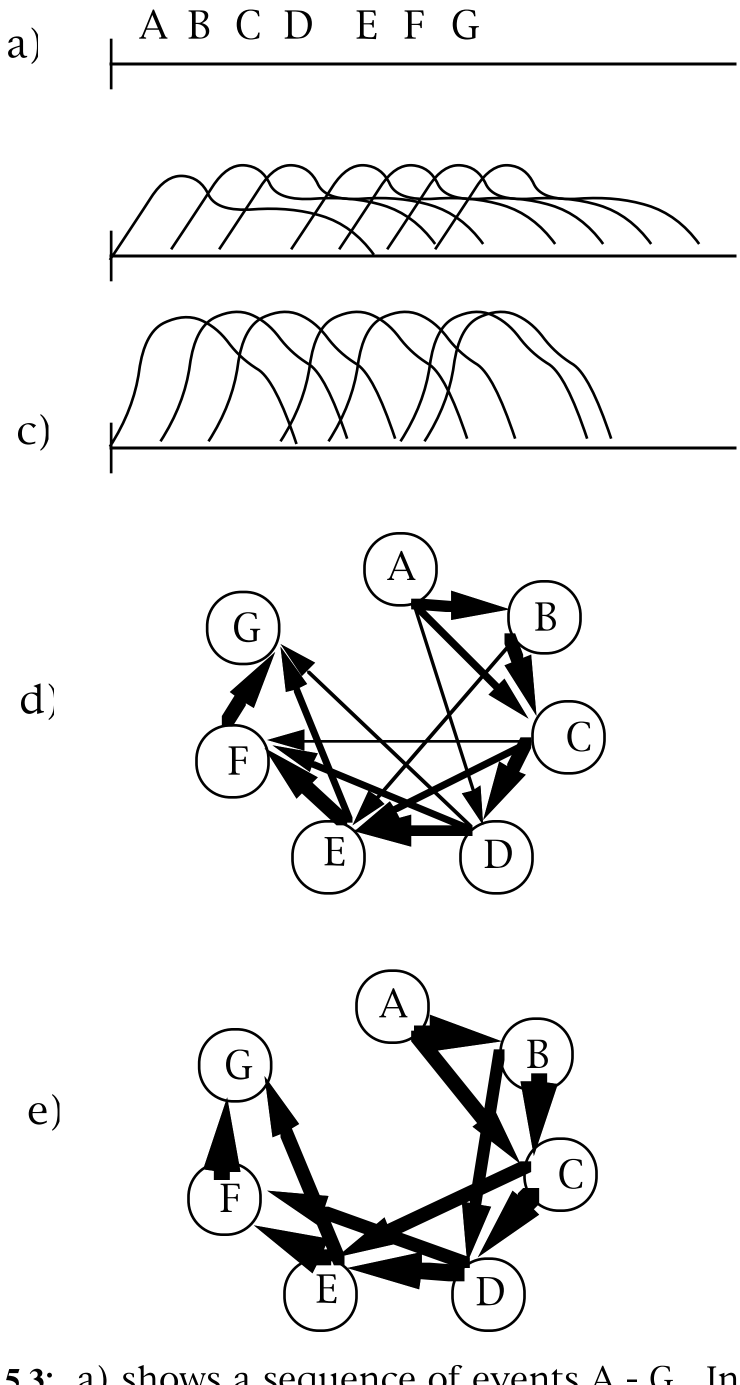

Figure 5.3: a) shows a sequence of events A - G. In b) high arousal generate consolidation periods. In c) high arousal generates shorter, more intense, c periods. d) shows associations formed with long consolidation periods and associations formed with shorter more intense periods. In d) there are more each of which is less strong on average than those in e).

The new sensitivity equation which includes arousal becomes

$$V(t) = \frac{\square A \square (L \square + \square S) \square (1 \square - \square F)}{n} \qquad (8)$$

where *A* is the arousal variable. Fortunately it is simple to incorporate TRACE results into this new equation by setting *A* to be unity. This also fits t description of TRACE which claimed to be modelling the activity of a cell asse ideal conditions. In terms of activity, ideal conditions means a maximum lev Some simulation runs showing different levels of arousal are shown in Table effect worth noting in the table is the relationship between LTCS and arousal arousal and LTCS are both a part of sensitivity their relationship is multiplica means that the competitive advantage that well learned cell assemblies have v greater under conditions of high arousal. From an adaptive standpoint this because it means that an organism will tend to resort to what is familiar duri (Wickens, 1987).

Table 5.3. Effects of arousal.

Arousal	Peak	Perception	Memory
	High long-term connection strength (l = 0.5)		
0.900	.678	13	66
0.925	.699	18	83
0.950	.720	25	111
0.975	.740	36	173
1.000	.759	52	427
	Low long-term connection strength (l = 0.5)		
0.900	.617	6	51
0.925	.639	9	71
0.950	.660	16	94
0.975	.680	24	138
1.000	.700	37	298

The left column contains the arousal value for each simulation run. The righ give the values of three dependent variables: the height of the peak of the Tl the duration of perception, and primary memory as measured by duration ii time step equals 10 msec.)

The results do appear to be slightly flawed since changes in arousal ap relatively large effects on duration as well as intensity. As it turns out, howe result of a breakdown in the mechanism which regulates duration, namely fa fatigue has been discussed and revamped a new version of this table will be which shows that with the revamped version of fatigue arousal has only a mi on duration.

Negative factors

Fatigue

The starting point for the examination of fatigue is the Kleinsmith effec The results attained by the TRACE equations do indicate that fatigue fills its c specified theoretical role in shutting down activity (Kaplan, et al., 1991). Eff fatigue serves to regulate the duration of activity in cell assemblies. But with of that role to include fatigue's critical part in accounting for the Kleinsmith be checked once again. The explanation for the Kleinsmith effect relies upon fatigue being associated with high arousal, versus low levels of fatigue when low. The role of fatigue, therefore, must now also include these factors. An of the behavior given the current model settings as shown in Figure 5.4 stro that fatigue does not behave according to the theoretical constraints. As the the amount of fatigue shows little variation with respect to the arousal level Table 5.3 shows, the quantity of activity is quite different. At these levels of differences after Kleinsmith intervals, such as 2 minutes, is negligible.

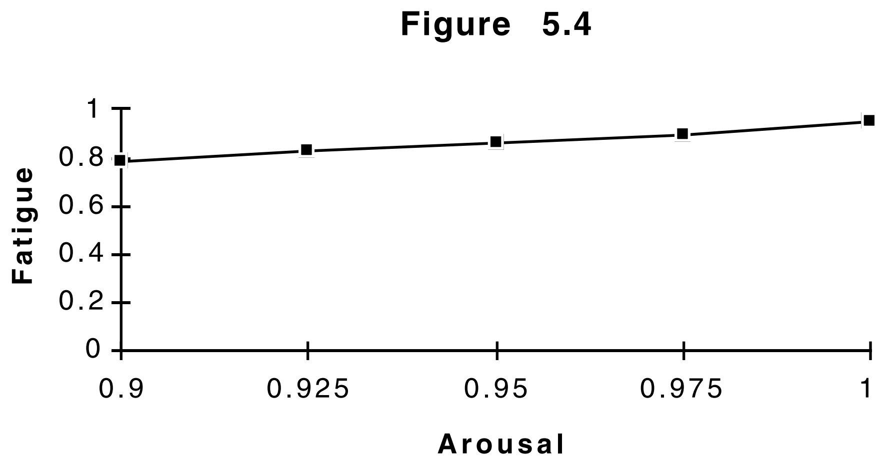

Figure 5.4: The graph shows the relationship between arousal and fatigue. E the differences in arousal generate significant changes in activity there is littl the final level of arousal.

The difficulty appears to lie in the rate of fatigue. In even the low arou fatigue grows very quickly, reaching a level quite near its maximum in less th second. A number of potential solutions were tried in an attempt to solve th The first idea was a two-tiered fatigue system based upon muscle fatigue. Th system has two sources for energy. One system is fast, both in expenditure a recovery, while the other system is slow. As a general rule muscles only use from the fast system except in extreme cases; but, when the load on a muscl draw energy from the secondary system. However, once the secondary syste the muscle essentially shuts down and recovery is very slow. This would ap reasonable explanation for what is happening in the cognitive system. One c that neurons have two energy sources, fast and slow, and that under certain such as high arousal, the slow system gets used. Unfortunately, while this d some differences in the final fatigue levels, under varying conditions of arou differences were not sufficient to warrant the change to the proposed system given that such changes resulted in other behavioral changes within the moc

prolonged periods of extremely high activity such as might be associated wit
Nevertheless the idea did seem promising and was not abandoned until an al
solution was found.

A second idea was that perhaps the results were not too far off and wh
was the fatigue recovery function. As it originally stood the recovery rate of
proportional to fatigue itself. The result is that highly fatigued cell assemblie
quickly and the recovery rate levels off as fatigue diminishes. Both the Klein
also the notion of a two-tiered fatigue system suggest a different approach.
approach builds upon the idea that it is more difficult to recover even a little
very high. This has the added benefit (with regard to the Kleinsmith data) th
small differences in fatigue might lead to more pronounced differences in re
With this in mind another series of experiments was run to test these ideas.
experiments the fatigue recovery rate was made proportional to (1 - F) instea
Further, the recovery rate was also tied to LTCS. This is based on the idea th
learned cell assemblies make more efficient use of their resources because of
internal connections. Although these results were promising enough to be in
into the final solution, they still did not change the original results enough to
for the Kleinsmith data.

Both of the ideas discussed so far have merit, but did not seem to addr
obvious part of the fatigue problem: the fast buildup. The direct approach t
is simply to change the growth rate of fatigue. Unfortunately this has a num
consequences on the model, mostly having to do with extended durations bo
perception and consolidation.

The next step was simply to examine the fatigue equation itself. The fa
STCS equations were given the least amount of examination in the original m
some degree were not strongly constrained by theory or data. After a great
experimentation with parameter settings within the model it had become clea

fatigue equation would need to be changed; the failure of the model necessit development of the theory.

Experiment 2: Simulating fatigue

The first step in the redesign of the fatigue equations was to drop the f altogether in the growth portion of the equation. After all, it is activity whicl resources and it is resource usage that fatigue measures. The fatigue level w included in the equation as a limiting factor, to ensure that fatigue never exc However, fatigue should never reach its maximum level since that would nec sensitivity to 0 and force a cessation of activity. The fatigue growth rate was to include a factor proportional to the connection strength of the cell assemb should reflect the fact that well learned cell assemblies are more efficient and will tend to stay within the neurons that make it up. The other straightforw redesigning fatigue was to change the recovery rate as already suggested. In these changes, one minor change was made to the short term connection str the exponent was again dropped in the growth term.

$$\Delta F = \phi_g P (1 - L) - \phi_d (1 - F) \qquad (9)$$

$$\Delta S = \sigma_g P (1 - S) - \sigma_d S \qquad (10)$$

The result of these changes was a system which still could not bring ab appropriate behavior within the model, but which was more manageable and more theoretically meaningful. It also turned out that dropping the exponen growth term was the key to discovering the ultimate problem with fatigue.

In the pure TRACE model fatigue has to build up quickly because it is e the only negative factor. There are two other negative factors within the mo only operate in the extreme conditions. There is the competition factor whic be influential only when activity is low and there is the dropout factor which be influential only when activity is high. There are no other negative factors This means that not only is fatigue responsible for shutting the cell assembly also responsible for the transition from perception to consolidation. Further only factor which does this. The result of such a system is that any time a ce becomes active fatigue must necessarily build up to the point where it can sh back down, even in cases of low arousal This means that even when arousal must be enough fatigue to shut off activity, and therefore such cell assemblie temporarily inaccessible. The real problem with fatigue in the TRACE model, that it is required to do too much.

As has already been discussed, one of the guiding design principles in in all of the SESAME models, is simplicity. One of the simplifications necessa TRACE was to treat the unit being modelled in virtual isolation. TRACE does input and includes a limited competition component, but it ignores effects th the interaction with other units. These effects can be direct, such as when o assembly inhibits another, or indirect, stemming from systemic control mech Arousal itself is a global control mechanism, but it is easy to incorporate beca activation can essentially be isolated from the activity of individual cell assen not true of some of SESAME's other control mechanisms. The difference is th of arousal is independent of the state of the system. The other mechanisms, hand, respond to such factors as the overall level of activity in a brain region respond to the activity of a number of cell assemblies they cannot be easily n the context of a single assembly. The reason that this is important is because global control mechanisms are inhibitory and the extra inhibition they provic solving the fatigue problem.

Inhibitory control mechanisms

The SESAME architecture provides for three types of inhibitory control: regional, and global. These are important not only because they directly imp consolidation, but also because they provide extra sources of negative impac assembly's level of activity, thereby potentially reducing the importance of f

Local inhibition

Local inhibition occurs between neurons in at least two basic paradigm often occurs as a part of perceptual competition (Is that a horse or a zebra?). inhibition will impact the speed of activation of a cell assembly. This paradig examined in some detail in the section dealing with input. In the second para inhibition comes as the result of interference from other cell assemblies[1]. Be of inhibition is extremely specific and has no general, predictable impact on t cell assembly no experiments were run.

Regional inhibition

Regional inhibition is a systemic control mechanism designed to preven concurrent activity within the system. Regional inhibition works on a simple principle: as the total activity in an area of the brain[2] increases, the regional that area also increases thereby decreasing the activity. The role of regional therefore is essentially as a mechanism to prevent the uncontrolled spread of situation which Milner (1957), who first proposed the mechanism, compared pile going critical. Regional inhibition can be implemented as a simple feedba mechanism similar to a thermostat. As the amount of activity in the brain re too great the regional inhibition level is raised and the inhibitory effect tends overall level of activity back down. Conversely, as the level of activity falls, t regional inhibition is decreased and activity will naturally begin to rise again

most prominent consequences of this mechanism is the magic number 5+-2[3]
number of concepts that can be active at any given time.

The effects of regional inhibition are not limited to specific cell assembl
inhibitory effect blankets an entire region of the brain. One of the effects of
inhibition within an area of the brain is that cell assemblies which are not yet
effectively be prevented from becoming active except when the input level is
this fashion the regional inhibition acts as a kind of contrast enhancement m
ensures that the signal to noise ratio of activity in the brain is at a reasonable
However, under conditions of high regional inhibition the activity of an indiv
assembly will also be affected. The effects are not entirely predictable becaus
reduced level of competition, but the major effect is certainly that any active
should be less active because of the inhibition.

Experiment 3: Regional inhibition

Modeling regional inhibition is not straightforward within TRACE. The
regional inhibition is dependant upon the state of the cognitive system as a v
single cell assembly. However, remembering that the goal of this type of sim
to build a perfect model, but to incrementally improve models in order to inc
understanding, an imperfect, but reasonable, solution was implemented.

The solution was simply to model the average case. Based on the idea t
cell assembly is active for five seconds and there are 5+-2 cell assemblies acti
given time, a simple model simply posits that a new assembly becomes active
while the activity of another dies out. Such a model gives an indication of th
within the system at any given time, and therefore the level of regional inhib
itself is an idealized model anyway, and the goal of these simulations was sin
that the principle of the combined effects of fatigue and regional inhibition w
was indeed sound. The implications of deviations from the average case are

important and will be discussed in the conclusion chapter in the section on f
the meantime the average case model was used to generate a curve which plc
level of activity within the system which corresponds directly to the amount
inhibition as shown in Figure 5.5. In the figure each of the curves in the low
represent the activity of a TRACE unit while the curve in the upper portion o
represents the summation of activity. This curve, therefore, should be an ap
the amount of regional inhibition within the system at any given time. This,
plugged directly back into the TRACE equation to model regional inhibition.
inhibition, like arousal should impact the sensitivity of a unit and as such it
a multiplier for sensitivity.

The results of runs incorporating the new fatigue and STCS equations,
regional inhibition are shown in Table 5.4. Because of the changes that have
other parameters settings were changed as well and are shown in the table.
system of equations a reasonable range of arousal was found to be from 0.5
arousal is lower than 0.5 the peak value does not reach what would be consi
perceptual level of activity. Further, when arousal is 1.0, and therefore equi
value in the original unmodified TRACE equations, the activity curve generat
the essential constraints of the original TRACE specification. It is also worth
that arousal no longer has a major impact on duration. Even the difference b
at its maximum and its minimum results in less than a ten per cent change ir
is evidence that fatigue is performing more efficiently in its role of regulatin

Another interesting effect is the contrast in activity found between high
connection strength and low long-term connection strength. It appears that
equations have even further differentiated the two cases. Under this system
cell assemblies stay active for approximately one and a half seconds longer w
well learned than when they are not. However, it is worth noting that despit
difference the change in the fatigue level generated is not dramatic, indeed w

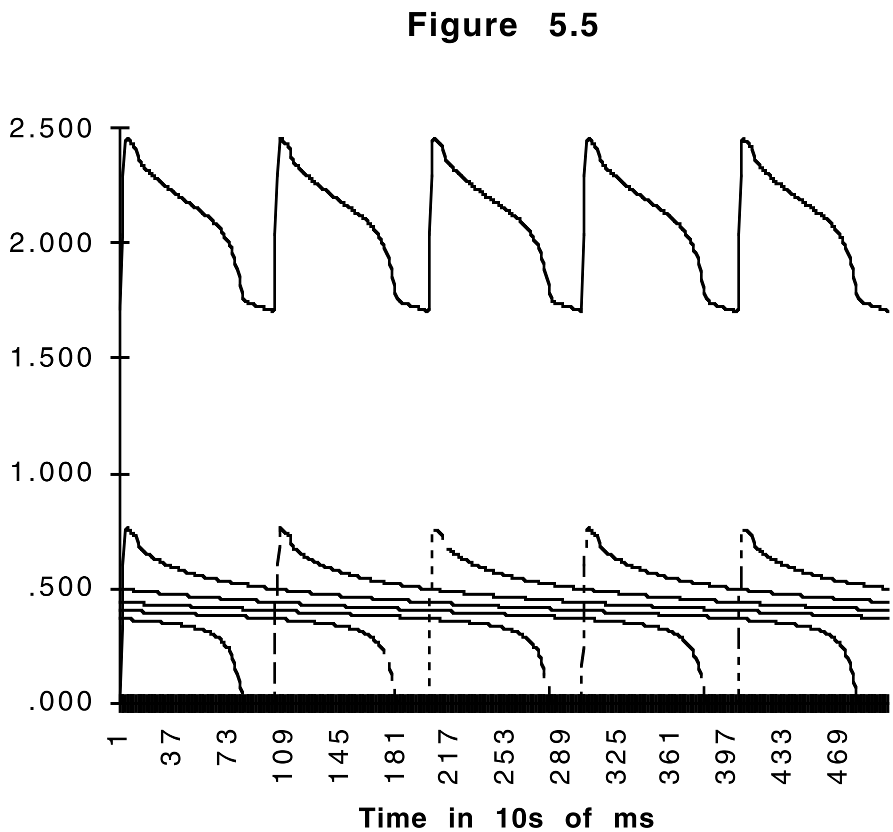

Figure 5.5: The curves in the lower portion of the graph are the individual T] curves. The curve in the upper portion is the summation of all of the curves represents the rise and fall of the total level of activity over time.

its maximum more fatigue is generated when the cell assembly is not well lea reason for this, of course, is that the fatigue rate is tied directly to LTCS, the that a well learned cell assembly makes more efficient use of its resources. O important next steps of this research is to study these interactions in more d this type of equation can generate reasonable learning curves to account for, the power law of practice. This issue is also closely tied to the duration ques since it impacts which cell assemblies will become connected to each other.

Table 5.4. Effects of arousal on new TRACE equations

Parameter	Peak	Perseverance	Fatigue
	High long-term connection strength (1 = 0.5)		
Arousal			
0.50	.621	502	.850
0.75	.713	486	.908
1.00	.812	459	.935
	Low long-term connection strength (1 = 0.2)		
Arousal			
0.50	.562	341	.826
0.75	.636	333	.902
1.00	.709	321	.938

Parameter	Interpretation	Unmodified val
θ_l	unit loss	3
ϕ_g	fatigue growth	0.007
ϕ_d	fatigue decline	0.0001
σ_g	short term connection strength growth	0.1
σ_d	short term connection strength decline	0.0001

The Perseveration column measures the length of time that the unit Fatigue column measures the strength of fatigue when the unit beca parameters shown are the only ones modified from the original equ

Global inhibition

Global inhibition is an attentional mechanism which works by uniforml the entire cognitive system. By itself global inhibition would simply uniform activity, but in conjunction with regional inhibition the effects can be quite s global inhibition tends to decrease activity, regional inhibition will necessaril response to global inhibition; as a result active areas of the brain will be rela unaffected by global inhibition since the net inhibitory effect will be minimal hand, in areas of the brain where there is little activity already, the net effect assemblies will be less sensitive to activation. The primary effect of global in therefore, is to prevent competition thereby allowing attention to be sustaine behavioral point of view global inhibition is an example of what James called attention.

In terms of consolidation the effects of global inhibition are far from cl one hand a new type of inhibition is imposed upon active cell assemblies, on hand, regional inhibition is decreased. Further because potentially competin assemblies are prevented from becoming active the net level of competition is decrease. However, it is extremely difficult to get a handle on how exactly al factors interact. For all of these reasons global inhibition was not modelled.

Input

Input, like fatigue and short term connection strength, was not well de theoretically in the original TRACE model. There are several reasons for this not clear that input needs to be well developed. James said that "perception probable and the definite." This does not mean that we perceive probabilitie that human perceptions are very definite and tend to reflect the most probab given input. The result is that the quality of input has relatively little to do w perception. On the other hand, James' statement reflects the fact that percep selective process in which the most likely percept given the input wins the cc consolidation terms this means that the intensity and duration of input shou relatively little effect on learning. Returning to the discussion of intensity an cell assemblies, the role of input is in an enabling capacity. Input in and of i have little impact on intensity and duration beyond the fact that it provides a function which can activate cell assemblies. All inputs which are sufficient to assembly should generate approximately equal activity curves. On the other differences in the quality of input should show up at the beginning of the act when the gating process is taking place. Roughly, strong input should indica match and relatively little competition, whereas a weak input might be indica match which is more likely to activate other, competing, cell assemblies.

Since cell assemblies can share features, any given input configuration stimulate a number of cell assemblies. James' analysis that perception is of t and the definite" provides insight into the results of this situation. Humans singularly; that creature is Fido, even though Fido may share a great many f other animals, the other possibilities do not come to mind. There are two im implications of this point in the present discussion. First, even though a nur cell assemblies may have been stimulated by the input configuration of Fido, perceived. This suggests a type of "winner take all" perceptual competition c connectionist systems. Second, even when the input to the cell assembly rep is relatively poor the perception will be strong. This implies that one import learning, and one that will not be dealt with here, is a kind of amplification t a poor stimulus to be strongly perceived. This amplification probably occur First, is through repetition. As a cell assembly is experienced repeatedly, the between the input cells in the visual system and the cell assembly are strengt be done using the same learning rule discussed in this dissertation. Second, of the cell assembly itself provides a type of amplification. In a well learned the strong internal connections are enough to activate portions of the repres directly experienced; seeing a part of Fido is enough to make one think of th

In terms of modelling cell assemblies the most important implication of is that the quality of input should have little impact upon the shape of the ac this is James' "definite." However, the analysis of competition suggests that may effect the timing of perception since the inhibition provided by competi

assemblies is likely to slow down the activation of the cell assembly eventuall
Rosch and others (Rosch, 1978) have done a number of studies which lend e
support to this analysis. The example most often cited is that it takes longer
that a penguin is a bird than it does to recognize that a robin is a bird. Presu
because penguins provide a poorer quality input to the bird cell assembly.

Experiment 4: Input and competition

TRACE, as the model stands at this point in the dissertation, meets the
but not the second, as is shown in Figure 5.6. Different levels of input (the c
figure represent inputs of sizes 1.0, 0.5, 0.1 and 0.05) generate nearly identi
curves. However, this is true even at the beginning of the curves where com
should be taking place. Further, it has been found that TRACE is exceptional
input, achieving perception even with inputs of extremely small amplitude.
be a problem, however, because TRACE is assumed to be modelling the cell a
under "ideal" conditions. Such ideal conditions include an input which is nc
across a number of cell assemblies and therefore would not foster much com

One simple way of implementing competition in TRACE might be to tie a
competitive inhibitory factor directly to the intensity of input. The idea behi
solution is that the cell assembly which wins the perceptual competition is lik
one for which the input is strongest; this suggests some type of relationship
intensity of input and the level of competition. It is worth noting, however,
intensity inputs need not necessarily generate competition since they might s
result of poor perceptual conditions such as fog or darkness. Such examples
there is an important distinction between the quality of an input and its inte
input may well be intense for other cell assemblies as well and, conversely, w
may be weak, it may be an extremely good match for a particular cell assemb
reasons competition cannot be tied directly to the intensity of input within T

However, experiments using such a test paradigm are worthwhile to see if TR
capable of generating the expected behavior when competition becomes mor

Figure 5.6

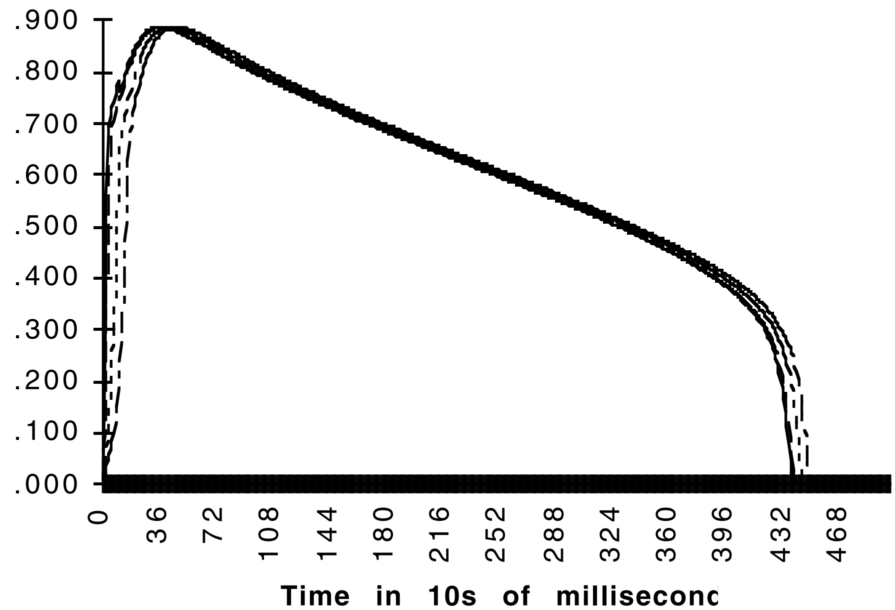

Figure 5.6: This figure shows the TRACE curves of four different runs superi over each other with inputs of size 1.0, 0.5, 0.1 and 0.005. Although the m the input is widely varied the curves are virtually indistinguishable from eac

After some initial experimentation the decision was made to restrict the competitive factor to the time while the input is on. The main reason for doi reflection of the process itself. For the cell assemblies involved in the percep competition there are two external factors affecting their level of activity: co input. When the input shuts off this leaves only the competitive factor. Rev cannot be a factor because it is so strong that once reverberation begins a pe activity is inevitable. Together this implies that only the eventual winner of t will reach a reverberatory level of activity. In the rest of the cell assemblies c is gone the only remaining factor is negative and the activity level in those ce

will quickly drop off to nothing. For the cell assembly being modelled, whic
to be the winner of the competition, this means that competition will also dr
other cell assemblies, however, competition will remain high as it will come f
assembly being modelled.

Competition is an inhibitory process similar to regional inhibition and
similar effects on a neuron's ability to fire. Therefore, the effect of this com
modelled in terms of unit sensitivity; as with regional inhibition this form of
interactive and therefore multplicative. The next question was how to model
of competition. There are two factors that appear to influence the level of co
cell assembly. The first is the intensity of input. As has been discussed ther
which show that intensity is not directly correlated to the quality of input, b
heuristic would be that in general more intense inputs will probably be of hi
The second factor in competition is the level of activity of the cell assembly it
assembly generates more activity it should more effectively supress competit
factors were taken to be compensatory, or additive, since either an extremel
a high level of activity by themselves will be effective in limiting competition.
factors are compensatory the level of competition is approximately equal to
(competition gets weaker as I and P grow large).

Since I and P can vary by orders of magnitude I was multiplied by a co
making the sensitivity multiplier ((c * I) + P); P was not modified by a const
relationship between activity and competition should be direct. This is not a
equation, however, since the value of competition can exceed 1; a value of 1
possible because it means that the cell assembly would become more sensitiv
of competition. To ensure that the value ranges between 0 and 1 the equatio
by dividing by (c + 1) * I. This extra factor grows large as the input grows la
ensuring that competition will never exceed unity. The net result of these ch
for the duration of the input, sensitivity was multiplied by ((c * I) + P)/((c +

reflect competition (the determination of the value of c was made by using a enough to keep the sensitivity at reasonably high levels). Some simulations different levels of input and LTCS are shown in figures 5.7 and 5.8. In each inputs of intensity 1.0, 0.5, 0.2 and 0.1 are used. Figure 5.7 shows the beg TRACE activity curves where LTCS is high and Figure 5.8 shows activity curv LTCS is low. One of the interesting effects to note is that it takes a more signi of input to activate a less well learned cell assembly than it does a well learne assembly (in point of fact, the level of input required is approximately 10 tin the low LTCS case). This reflects the fact that it is simply easier to identify th familiar. Further, the competitive factor means that the time taken to identif vary according to input quality. In the penguin example a penguin would pr poor quality input to a "bird" cell assembly and therefore would activate it m a robin might.

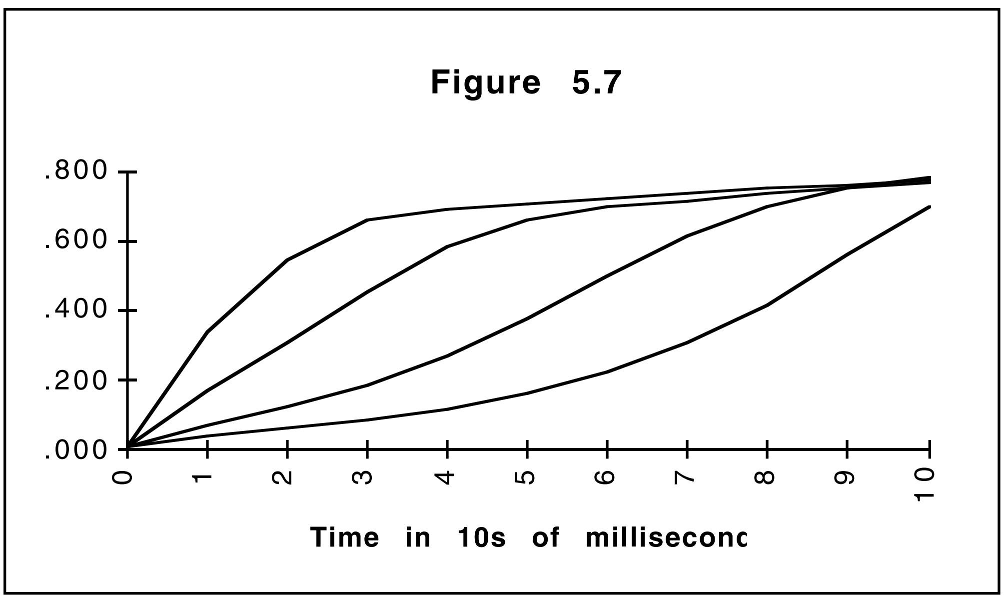

Figure 5.7: The figure shows the time course of activity over the first 100 mil for different inputs when LTCS is high (0.5). The strongest input results in t increase in activity.

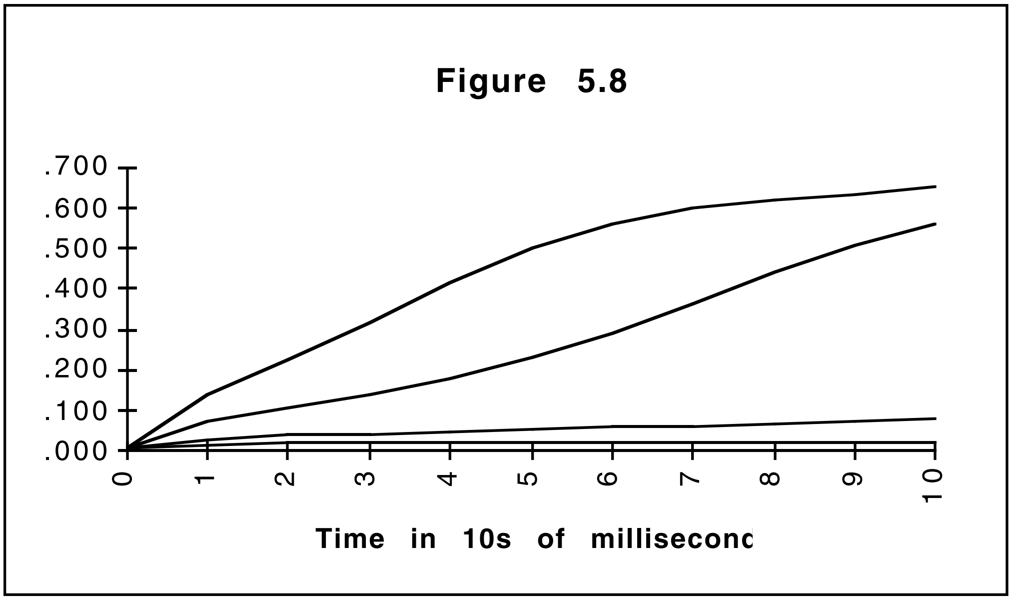

Figure 5.8: The figure shows the time course of activity over the first 100 mil for different inputs when LTCS is low (0.2). The strongest input results in tl increase in activity. In this case the two weakest inputs do not provide enou the cell assembly to reach a perceptual level of activity.

The input experiments, as well as the regional inhibition experiments, : the power and some of the weaknesses of a model like TRACE. The simplifica make TRACE useful also mean that some of TRACE's behavior will necessarily of theory. On the other hand, when the context of TRACE is kept in perspect possible to design experiments which show that the shortcoming are not witl itself, but are due to the simplifications. These experiments can not only fur understanding of the model, but can provide significant insights into the nex models. For example, when TRACE units are put into a more global context, the MultiTRACE model, the regional inhibition insights can be used in the de: regional inhibition control mechanism. Conversely when a lower level versic assembly model is designed, for example one which simulates perceptual cor insights and results from the input experiments should be useful. Even thes be taken as "correct" however, since they too are approximate. However, th that TRACE is capable of generating reasonable behavior within the confines cognitive theory. As such, the results can be used as a starting point from w iteration of the successive approximation strategy can begin.

Summary of the TRACE model and consolidation

The various components of TRACE and their effects on consolidation ar summarized in Table 5.5. In examining these factors a general portrait of lea drawn. In the discussion of credit assignment, contiguity and repetition wer A thorough examination of learning in TRACE also shows the premium placed two factors. The basis of the learning rule is contiguity, in this case the cont firing. In the next chapter it will be shown that contiguity plays even further learning.

Table 5.5. TRACE parameters and consolidation

Factor	Impact on Consolidation	Role
LTCS	Positive	Mechanism of reverberation
STCS	Weakly positive	Short term memory
Arousal	Variable	Enables "importance" to impact consolidation
Fatigue	Negative	Limits perseveration
Regional Inhibition	Negative	Limits activity
Local Inhibition	Negative or none	Competitive factor

The leftmost column lists TRACE model parameters. The middle column sho parameter's relative effect on consolidation. The final column lists the theor factor plays in TRACE.

Repetition is a primary factor in learning at both the molar and molecu the molar level repetition is reflected in the LTCS level of a cell assembly; the cell assembly has been active the higher the level of LTCS. The level of LTCS impact upon learning because it facilitates prolonged activity. From an adap the "goal" of credit assignment is to learn about important things. Frequenc indicator of importance; it is important to know about things one often com with. The analysis is similar at the molecular level. In this case the repetitio individual neural firing patterns. The more times one neuron fires another t is that the pattern is more than a mere coincidence. The factors in TRACE wh a direct impact on consolidation give the cognitive system a method of evalu importance and translating it into learning by controlling the amount of repe molecular level.

To see how learning in TRACE works it might prove fruitful to run thro simple example. It is the position of this dissertation that an event in the wo represented in the head by the sequential activation of a series of cell assemb active cell assembly corresponds to some object (whether concrete or abstrac object is sensed the cell assembly representation of the object becomes active competitive perceptual process. Although this competition might appear to i consolidation since it involves inhibitory mechanisms which suppress activit negligible impact upon the ultimate strength of learning for the cell assembly becomes perceived because once reverberation begins it is extremely strong r impact of perceptual competition. However, the activation of the cell assemb the resulting reverberation, does set the basic learning heuristic in motion. A heuristic is defined by how strongly the neurons in the cell assembly are con in the TRACE equations) and the rate of fatigue of the cell assembly, which to determine how long the cell assembly will remain active. In general cell asse remain active for several seconds; for example, a well learned cell assembly consolidate for approximately five seconds. Left alone the consolidation pro strengthen the internal LTCS of the active cell assembly as well as stengthen i to other active cell assemblies. This strengthening takes place due to the acti learning rule which essentially increments the strength of connections betwe when they fire contiguously.

While the cell assembly is active any number of things can occur which direct impact upon learning. Perhaps the most important such event is a cha To some degree arousal is a direct measure of importance or the human equi evaluation function. Signals such as pleasure and pain trigger changes in aro allow the basic learning heuristic to be altered. Whereas the dominant influe strength of learning is normally molar repetition, arousal allows for this proc circumvented through an exceptional degree of repetition at a molecular leve

Returning to the credit assignment issue, a general perspective on learn domain is possible. Initially learning within a new domain will be slow as str up. Learning can be accelerated at times by high levels of arousal, potentiall directly by pleasure or pain, or indirectly through clarity and confusion, but part repetition will be the dominant factor in what is learned. As experience domain increases, the cognitive system's impact on learning will increase. So impact will come in the form of inhibitory suppression (a likely reason for w eventually slows down within domains). More interesting may be anticipato Because the system is based upon sequence it is built for prediction. Among predictions that can be made are that pleasure or pain is likely. For example is associated with a pleasurable outcome, and situation A leads to situation B predictive system will learn to associate situation A with the pleasurable outc anticipatory association can actually serve to raise the level of arousal when s experienced (Figure 5.9). This kind of backward chaining is exactly how sys Bucket Brigade algorithm and Samual's checker player function. Just as Sam player codes states according to their potential for winning, so too can the co code states according to their potential to bring positive or negative results. anticipatory coding can be compared to Pavlov's dogs salivating at the sounc

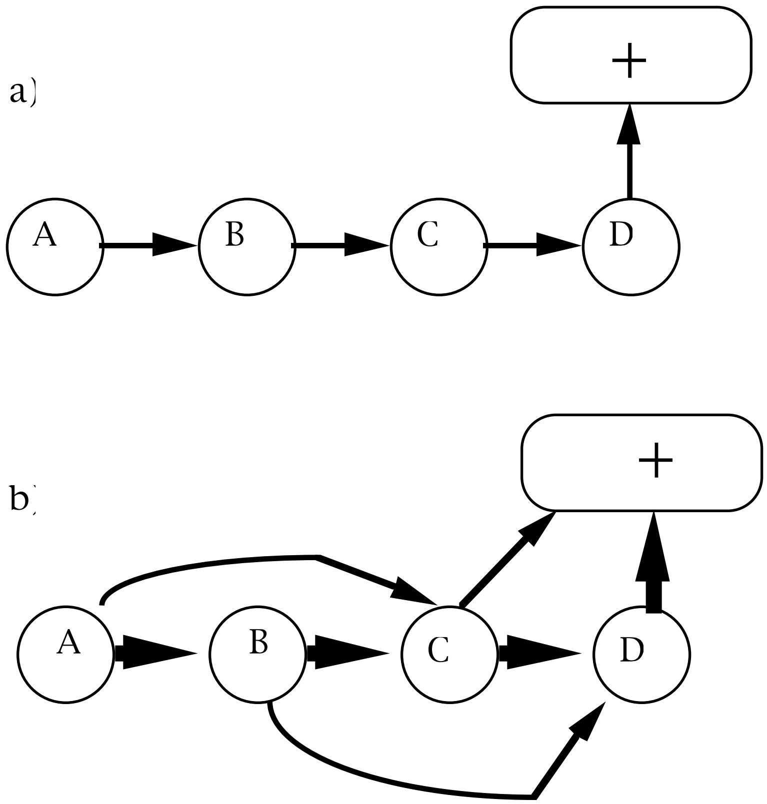

Figure 5.9: In a) the sequence A - B - C - D, which leads to a positive outcome been experienced. The circles represent cell assemblies and the arrows betw represent associative connections with the width of the arrows indicating rel In b) the sequence has been experienced again, and further connections can this case the positive outcome can be directly anticipated when C is reached. sequence is experience enough times, only A will be required to anticipate th outcome.

This discussion has strayed somewhat beyond the level of a single cell In the next chapter I will show how consolidation can be used to build up the associative sequences just discussed. This will lead to further refinements of rule as well as a close examination of the Kleinsmith paradigm.

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[1]This type of inhibition might come as the result of the learning ru SESAME it is presumed that the output capacity of a neuron is fixed. Therefo connection between two neurons is strengthened another is necessarily weak arrangement solves a number of problems inherent in Hebbian-style learning outside the scope of this dissertation. It is possible that weak connections mi become inhibitory. While this is still an open question it helps to explain eff certain kinds of psychological interference.

[2]The physical location of activity is important in the SESAME archit
The guiding principle is that cell assemblies that code similar things will be cl
the brain. Further, loci of activity that are near each other will tend to interf
other (Kinsbourne, 1982). This principle is critical in explaining such conce
perceptual competition. It also plays a key role in learning and will be discus
later chapters.

[3]In 1956 there appeared a paper by George Miller entitled "The ma
number seven, plus or minus two: some limits in our capacity for processing
Due to this insightful and frequently cited paper, it is widely believed that pe
7+/-2 units of information in working memory. The metric Miller adopted, l
the threshold, defined as the point halfway between chance and perfect perf
one is interested in the number of units people can *accurately* hold in working
(i.e., without error), then the correct value is, as Mandler (1975) has pointe

CHAPTER 6

SIMULATING THE KLEINSMITH EXPERIMENTS

The purpose of Chapter 5 was to show that the consolidation model em TRACE is capable of differential learning responses over a range of theoretica meaningful situations. In most of these cases, however, since TRACE isolates of the cell assembly modeled from the rest of the cognitive system, such resp contingent upon events external to the cell assembly. To this end several of run in Chapter 5 relied on average case modelling. This is a reasonable appr a rudimentary understanding of the model's functioning with regard to the l is not, however, a replacement for embedding the model in a larger system; exists and is called MultiTRACE (Sonntag, 1992). MultiTRACE is a simulation to do sequence learning within the cell assembly framework by modeling a la of cell assemblies. As such it is well suited for testing consolidation because primary modes of learning in a system with a consolidation-based learning ru sequential. Further, sequential learning is essential to establishing the linkag consolidation and arousal because paired-associate tasks such as the the one Kleinsmith paradigm are essentially two element sequences. While MultiTRA attempt to simulate the entire cognitive system it represents a significant step which is modelled by TRACE, providing, for example, the direct ability to mo such as regional inhibition.

To this point in the dissertation there have been two important themes consolidation is one of the primary means of human learning, and second, th consolidation, as embodied in the human learning system, is a powerful, gen

mechanism capable of differential learning even in novel domains. The Klein
are central to establishing both of these points. First, while no one appears t
consolidation exists, some do question its relevance to understanding learnir
effectiveness, viewing it merely as a by-product of the learning process. The
this dissertation, by contrast, is that the consolidation process and the effect
learning are inexorably linked. The Kleinsmith results are critical in making
because the explanation of the Kleinsmith results proposed here relies upon
of consolidation. In addition, if such a theory of consolidation makes a simu
Kleinsmith results possible, it gains credibility by virtue of being the only mo
kind to do so. Once established, this relationship between consolidation and
effectiveness of learning can serve as the basis for understanding the power
consolidation, even in novel domains, because the factors which impact cons
arousal being one, do so in theoretically significant ways.

For these reasons modelling the Kleinsmith results is the main goal of t
as well as the single most important experiment in this dissertation. Unfortu
MultiTRACE cannot be used directly because of the modifications already ma
TRACE equations. MultiTRACE was designed and tested in accordance with th
model circa (Kaplan, et al., 1991). Because of this, therefore, before the Klei
experiments can be simulated, MultiTRACE must be updated to reflect these c
Further, and more importantly, the additional constraints imposed by the ne
modelling the Kleinsmith results led to additional model development.

Short term connection strength

One of the changes made to the original TRACE equations was to modif
term connection strength (STCS). In MultiTRACE, STCS has two functions. F
appears in the equations for simulating the individual units in accordance wi
model. Second, there is an inter-unit form of STCS which is based upon the

principle as intra-unit STCS of the type found in TRACE. However, while the of inter-unit STCS may well be the same as for intra-unit STCS, its functionin appear to be quite different. Whereas intra-unit STCS allowed even loosely c assemblies to become active by providing extra connection strength to facilit reverberation, inter-unit STCS appears to be more involved in the reactivatio assemblies, providing a kind of short term memory.

STCS and short term memory

Inter-unit STCS is an attractive candidate for an explanation of short te for several reasons. First it does not require the proposal of a new mechanis mechanism involved in intra-unit STCS could reasonably be hypothesized to functions. Second, its role as an enabling mechanism for the activation of ce is functionally equivalent to what is needed for a short term memory mechar the role of intra-unit STCS was to enable the initial activation of a cell assemb proposed scheme the role of inter-unit STCS would be to enable the reactivat same cell assembly. In the general case cell assemblies are experienced in se (Hebb, 1949; Kaplan, et al., 1990; Sonntag, 1992) and an important aspect the ability to recreate those sequences. The role of inter-unit STCS in such a therefore, would be that when one or more elements of a sequence have bee facilitate the activation of the next element. Another reason why inter-unit S for such a function is that its time course is temporary, as it would need to b term memory mechanism. In total, STCS is a strong candidate for a short ter mechanism because it provides the needed functionality within the framewo developed.

Correctly functioning inter-unit STCS is critical to the ability to simulat Kleinsmith results. The paired associate task used in the Kleinsmith paradig a two element sequence. The recall test is to present the first element and re subject to generate the second element. In this respect at least the Kleinsmitl should provide a useful step towards generalized sequence learning. Since tl which should account for the ability to reactivate the second element is inter (this will be discussed in more detail later) the Kleinsmith paradigm should b isolating its effects. This is more difficult in the general case since most sequ multiple elements, more than one of which can affect the activation of subse Therefore the isolation brought about by restricting the sequence to two elen allow for a more careful study of STCS.

The mechanism of STCS

Though it is possible that the same mechanism that is responsible for S TRACE could account for inter-unit STCS in MultiTRACE, it is not immediately this may be the case. One of the advantages of a model like TRACE which mc aggregate populations, is that some of the details of the underlying mechanis specified as is the case with STCS. However, inter-unit STCS in MultiTRACE, of the interactions between components, requires a further specification.

To review, the role of STCS in TRACE was to provide a temporary incre connection strength among the units of a cell assembly in order to facilitate r This increase in connection strength serves to allow the units of a cell assemb efficiently fire each other even when LTCS is relatively weak. There are two c how this increase in firing efficiency might come about, based upon whether mechanism is sensitive merely to activation, or to particular patterns of activ case active neurons become temporarily more efficient in their ability to fire In this case if a neuron has recently been active then it will temporarily be m firing all of the other neurons to which it is connected; since this increase in generalized this can be called a nonselective mechanism. In the second case not generally more efficient, but the specifically effective connections betwee become temporarily more efficient. In this case if neuron A helps to fire neu connection between them becomes temporarily more efficient. As a result ne more effectively facilitate neuron B's firing for a short time thereafter. Howe neuron connected to B fires it will not be more efficient because the increase was only from neuron A to neuron B. Since the increase in efficiency is speci case, this is a selective mechanism.

In the SESAME framework, as reflected by Sonntag's implementation, S always been considered to be a nonselective mechanism. However, a theoret examination of STCS strongly suggests that the selective interpretation is cor

The nonselective version of STCS is adequate to deal with certain types problems as Sonntag showed. For long term learning experiments where rec measured after STCS has dissipated the form of STCS is not relevant. The fo even be strictly relevant for certain types of short term recall experiments. T any cell assembly that has been active will have a high level of inter-unit STC might appear be sufficient to give it a competitive advantage versus other cel This is where the Kleinsmith paradigm becomes crucial in understanding the STCS. The Kleinsmith data shows that this temporary increase in inter-unit S becomes effectively negated under certain conditions. Further, the examinat TRACE model has revealed that the buildup of fatigue in virtually any cell ass enough to counteract the effects of intra-unit STCS, effectively decreasing the the cell assembly until it shuts down. Therefore, in the general case, a recent assembly will be less sensitive to being activated, based purely upon its inter other cell assemblies. All else being equal, therefore, recently active cell asse least likely to be associatively activated, providing the system with a type of a It follows that there must be some compensatory factor which can account fo memory.

The compensatory factor, of course, is inter-unit STCS. Just as intra-u provides a temporary boost in connection strength to compensate for a lack unit STCS can provide a temporary boost in connection strength to compens However, if STCS is nonspecific it might still provide a type of anti-memory. cell assembly is reactivated under such a paradigm it will tend to efficiently a cell assembly that it is connected to. However, since the target cell assembly in the original sequence is less sensitive due to fatigue as discussed in the pr paragraph, it is highly unlikely to be reactivated versus all of the other cell a which are not fatigued at all (Figure 6.1). This can be partially alleviated by dissipate rapidly, but the Kleinsmith data show that fatigue lasts at least for minutes. This problem does not arise when STCS is selective. In this case th assembly will only tend to activate the cell assemblies that were active concu originally. This selective increase in STCS can serve to compensate for the de sensitivity of the target cell assembly (Figure 6.2) by boosting the active cell ability to activate the target cell assembly.

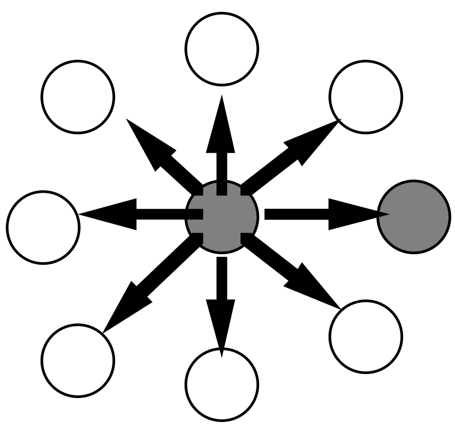

Figure 6.1: The circles in the figure represent cell assemblies. The center circ circle to its immediate right correspond to two elements in a recently experie The shading represents the fact that the elements are relatively insensitive to to their fatigue levels. The lines represent the combined influence of short-te term connection strength. The cell assemblies surrounding the center repres assemblies connected to the center one (the actual number would be much la cell assembly in the center were to be reactivated it would probably not react assembly to the right as the next element of the sequence because that cell as fatigued.

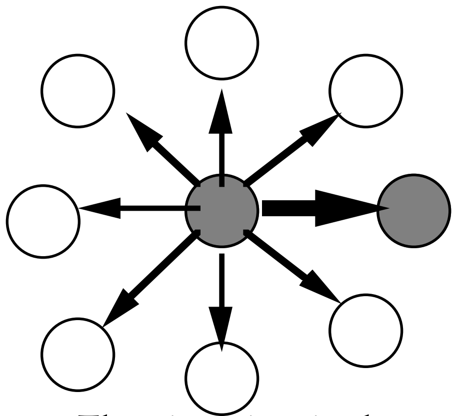

Figure 6.2: The situation is the same as in Figure 6.1. However, in this case selective and therefore only the shaded cell assembly on the right gets extra i center cell assembly which is why the connection into it is so much stronger. connection strength can compensate for the cell assembly's decreased sensiti recall of the sequence possible.

Such a change also serves to help alleviate one the of major problems t faced. Sonntag run numerous experiments which showed that controlling ac of the most difficult challenges in making MultiTRACE work. Changing the fo STCS has a dramatic effect on this problem. Since cell assemblies no longer h temporary increase in their capacity to fire every cell assembly they are conn effect of an active cell assembly on the cognitive system as a whole is greatly Where an active cell assembly in the original version of MultiTRACE essentiall the system with input, it now only impacts specific other cell assemblies.

From a credit assignment perspective the proposed change is also reas credit assignment model proposed in this dissertation is based upon changin between elements when they have strongly correlated activity. The updated STCS reinforces that importance within the system. One of the purposes of s memory might be to provide a kind of rehearsal effect where an organism ca in its head in order to strengthen learning; the rehearsal serving as yet anot repetition. If, in the course of rehearsing these events, the organism were to the original sequence, as would easily be the case with the previous version would greatly interfere with the learning process of the experience. The new STCS helps to ensure that the sequence will be re-experienced without deviat

Summary

A mechanism for short term memory is crucial for the ability to simulat Kleinsmith paradigm. Such a mechanism, STCS, was already in place in Mult but a closer examination of its role in the light of the Kleinsmith data showec version of STCS to be inadequate. Fortunately a change in the understandin mechanism of STCS was able to address these shortcomings. This change inv hypothesizing that STCS is a selective, rather than a non-specific, mechanism did not necessitate any redesign of the TRACE model and only required a sm MultiTRACE. Further the changes to MultiTRACE address additional problem its original designer.

The learning rule

The Kleinsmith results (and a number of other studies) predict a simpl between long term learning and arousal: as arousal increases learning impro theory proposed in Chapter 5 used the relationship between activity and lea this. To simulate it in MultiTRACE requires a learning rule which can vary th learning according to the quantity of activity. In developing MultiTRACE Son have to address this directly. The issue he was working on was whether or n MultiTRACE was capable of effectively learning sequences. Since he was not a to match any specific learning data, and since arousal, the major source of ac variation, was not yet included in the TRACE model, he was able to use a qua version of the learning rule. This original rule divides the activity of a cell as three phases corresponding to latency, perception and consolidation and on learning to occur when one cell assembly is in the consolidation phase and is another in the perception phase. In simply proving that the principles work reasonable solution. However, to explain the reminiscence data a further spe the learning rule is necessary.

There is other learning data available, data related to the Kleinsmith pa which also provides insight into the specification of the learning rule. One o known problems of an associative learning rule, such as the Hebb rule, whicl the basis of the MultiTRACE learning rule, is sequence direction. If two cell a are firing simultaneously then presumably connections are being strengthen the other (Figure 6.3). However, it has been shown that humans generally s learning in the original sequence direction and only weak learning in the opp This and similar difficulties that associative learning models have with tempo been called one of the fundamental problems of associative learning (Miller a 1993). Including this data might seem to be a violation of one of the modelin set forth in this dissertation, that models should be kept as simple as possibl moving on to more data. However, this data is relevant to the Kleinsmith res the solution hypothesized here provides further evidence for the fatigue con

The first change to the qualitative learning rule originally used in Multi that the neurons within a cell assembly cannott "know" whether or not they consolidation or perceptual phases. There must necessarily be some physica between the two states if such a learning rule is going to be proposed. The c candidate for this difference is fatigue which, under the revised equations, fa reflects the period of time that a cell assembly has been active. The consolida states that important events are learned better because the amount of activity activity can be "read," or inferred, from the level of fatigue. To this end Heb learning rule, which specified that when A facilitated the firing of B leads to a of the A->B bond, should be amended to include fatigue.

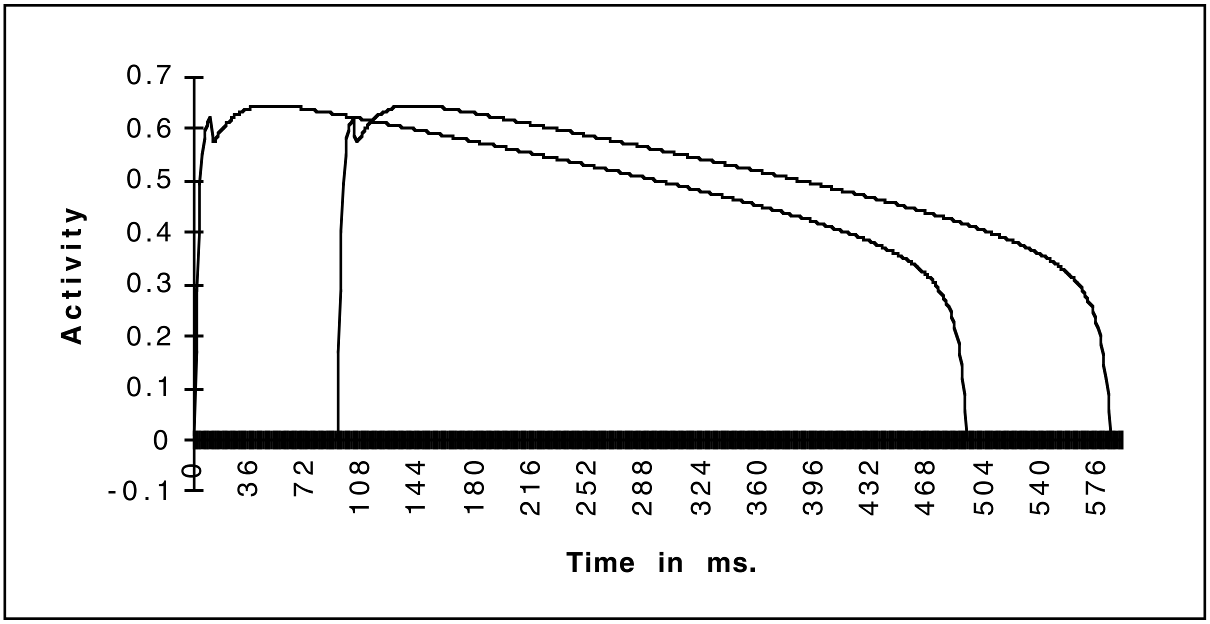

Figure 6.3: The figure shows the time course of activity of two cell assemblies sequence. During the time period in which both are active, a period of abou neurons in the first cell assembly will fire simultaneously with neurons in the assembly. In a strictly associative learning rule such as the Hebb rule, such a result in strong connections from each cell assembly to the other.

Recalling the credit assignment discussion, repetition is an indicator of and the repetition of neural firing leads to higher and higher levels of fatigue since the fatigue level of a cell assembly is directly correlated to firing repetit that the higher the level of fatigue the greater the change in strength should reasoning will be discussed in far greater detail later in the chapter). The ne therefore, emphasizes not only the correlation of activity between cell asseml fatigue of each one. First, learning does not begin until the cell assembly has threshold of fatigue τ. Once the cell assembly has reached that threshold the $\varepsilon P_1 P_2 F_1^{\pi}$, where ε and π are constants, P_1 and P_2 refer to the level of activity respective cell assemblies and F_1 is the fatigue level in the first cell assembly.

With such a rule, learning will become faster as a cell assembly grows r fatigued. This amendment is also attractive because it provides a solution to sequence direction. In a sequence the various active cell assemblies will be in states of fatigue. For example, in a sequence A - B the cell assembly for A wil somewhat fatigued by the time the cell assembly corresponding to B become: the new learning rule the change of strength for units in A firing units in B (/ relatively large compared to units in B firing units in A (B->A). Further, beca addition of fatigue to the learning rule, it is no longer the case that simultane of cell assemblies will yield maximal learning. In a pure contiguity rule such rule, learning will be maximized when two events occur simultaneously becau be a maximum correlation of activity between the two representations. Howe adding fatigue to the learning rule this is no longer the case; learning will te maximized when the first cell assembly is becoming fatigued when the secon assembly is at a peak level of activation. Miller and Barnet (1993) support su reviewing evidence that shows that simultaneous conditioning is relatively in comparison to the spaced case.

The Kleinsmith paradigm

To this point in the chapter, several important changes in MultiTRACE l discussed, but without reference either to experiments or to relevant equatio parameter settings. In reality numerous simulations were run along the way the changes seemed plausible, but each set of changes meant changing most from the previous iteration. The data that can be used to check all of these c as the underlying reason for making all of these changes in the first place, is data. The two major changes to MultiTRACE, modification of STCS and the le were required due to the theoretical demands of the Kleinsmith data. The or rule could not account for changes in activity levels brought about by variati and had to be modified, and the STCS changes were also as a direct result of model's inability to handle the Kleinsmith data. Once these changes were in

possible to experiment with the simulation to see if a set of parameter setting
permitted reasonable modelling of the Kleinsmith effects.

Experiment 5: The Kleinsmith paradigm

The Kleinsmith paradigm involves giving subjects pairs of items while r their arousal levels. Recall is later tested by presenting the first item in the p condition being a determination of whether or not the subject can recall the s the pair. The data were analyzed by sorting the items based on the level of a time of initial presentation. The high versus low arousal cases were determir within-subject basis, by taking the lowest scores for a given subject as low ar versa, rather than by an absolute measure.

Simulation Procedure

For the most part the mechanics of the Kleinsmith paradigm are simple in the new version of MultiTRACE which shall be called MultiTRACE2. The or presentation of the items consists of presenting inputs to specific units at the interval. The recall condition involves presenting an input to the first unit ar see if it can activate the second unit through its associative connections. The events can be precisely handled since a single step in MultiTRACE2 takes 10 r In MultiTRACE2 there were two recall conditions tested corresponding to test minutes after the initial presentation and one day later.

Because of the difficulties in determining exact parameter settings, and of changes in the original experiments themselves (such as using nonsense sy and words in the other), the goal in running the Kleinsmith simulations was replication of the original results but rather a match to the original pattern. ' number of factors which will impact the results of the simulation, one being t pattern of connections within the network, which are not easily modelled. F is not known exactly how cell assemblies are connected; and the issue is furt complicated by the fact that learning is essentially a rewiring process such th connections often changes. The result of learning, therefore, is a new patter connections which will have inevitable effects on future patterns of activity. the Kleinsmith data completely would require some knowledge about the gen connections between cell assemblies. Kleinsmith and Kaplan addressed this degree in their second set of experiments which used nonsense syllables (19 nonsense syllables are unlikely to have participated in any sequences, the co of the cell assemblies which represent them are not likely to have ever chang still further complicating factors, however, such as the fact that any given ce not connected to every other cell assembly. This means that certain associat cannot be learned in a single presentation. This too will affect the results an known what the percentage connection rate is, so it is impossible to tell what the effect will be. One hint does exist within the Kleinsmith results however, peak performance in both the low and high arousal cases never gets much ab percent. This might indicate that there is about a 60 percent connectivity rat assemblies within a given cognitive level. However, none of this is a certaint reason exact replication of the Kleinsmith results cannot be the primary goal simulations.

Another difficulty in replicating the Kleinsmith results comes in decidi handle arousal within the simulation. Experimental monitoring of a subject's indicates that there is a baseline level of arousal which is deflected up and do To replicate the Kleinsmith results in a simulation it is necessary to determin baseline level of arousal might be, what reasonably sized deflections might b the level of arousal should be at recall. It is difficult to solve such problems through trial and error simulation, that is, running the simulation with diffe determine what appears to be reasonable behavior. Simulations of this type

as modelling specific data, but instead are designed to determine what reaso
might be when the actual simulations are run.

The baseline level of arousal for the Kleinsmith simulations was determ
finding a minimum level of arousal and splitting the difference between that
maximum arousal, which has always been set at unity. The minimum level c
determined by finding the level of arousal necessary to allow a weakly conne
assembly to achieve a perceptual level of activity. Lower levels of arousal wo
comatose state where nothing was perceived. Both the problems of arousal c
arousal level at recall were handled by systematically varying the levels of ea

Rather than attempting to simulate subjects by randomly generating ne
corresponding to each subject, the approach taken was to systematically moc
such as arousal in order to isolate their effects on performance. Further, all
done on pairs of connected cell assemblies since a negative result will always
the cell assemblies are not connected.

The Kleinsmith paradigm essentially breaks down into two cases: short
and long term recall, which is reflected in the two simulation cases where rec
the order of a few minutes and on the order of a day. The important factor i
case is the amount of learning. Because STCS and fatigue should dissipate in
hour residuals levels of each should not be a factor. Further, since the time
secondary consolidation is similar, it too should be complete. For the long t
therefore, instead of running the simulation for a day or a week of simulated
simulation was simply reset once learning was complete. The effect of resetti
simulation is that fatigue and STCS are cleared back to their original state.

The straight Kleinsmith format of testing for recall at a two minute inte
used because simulations like MultiTRACE2 are capable of more informative t
different test paradigm was used which involved discovering what the critica
when recall first becomes possible. For example, when arousal is at low level

not be possible for a minute or so until fatigue dissipates, whereas when aro
levels recall may not be possible for three or four minutes. This is more info
simply testing for recall at a two minute interval since it not only yields the r
two minute case, but also the minimum recall times, and it gives a better pict
corresponding recall curves are.

The test paradigm used was simple and involved fixing a testing level o
and then using that level to determine the minimum length of time needed b
possible. In order to do this a new network was generated for each test whic
the basic Kleinsmith paradigm with varied recall intervals. So, for example, i
case the minimum level of arousal was used, a new network was generated a
Kleinsmith paradigm was run for some small interval time. If recall was not
interval was increased, another network was generated and the procedure w
This process was repeated until a minimum recall interval was found. At this
arousal level was increased and the procedure was repeated.

Another difference in the short term case was that learning was shut of
reason for this has to do with the data on secondary consolidation which ind
chemical changes that take place during learning take on the order of 30 mir
Recall times on the order of two minutes are not sufficient for the learning p
completed. Such a test also has the advantage of minimizing the number of i
factors affecting the results.

The remaining major issue is what the level of arousal should be at rec
these simulations the baseline level of arousal was used since it represents a
value[2].

Results

Successfully simulating the Kleinsmith paradigm results are essential i
approach to credit assignment developed in this dissertation in two importa

such simulations can help to establish a linkage between the strength of learı consolidation by showing that consolidation is the mechanism which translat learning. And second, they can provide further evidence for fatigue as well potential usefulness in the learning context. Because the results are so vital t of this work it is worth reviewing the two critical issues that the simulation m successfully address.

The first issue, and the crux of what makes the Kleinsmith data so diffi explain is the pattern of the short term results. There are two important poi this pattern. First the data show reminiscence; that is, that recall performan improves with rest. The reminiscence data absolutely cannot be modelled wi time dependant variables. Further, the short term data also show that when recall is difficult, if not impossible, during the first two minutes. On the oth arousal is low, recall is excellent after two minutes. The only factor which ca both of these points in the SESAME system of models is fatigue[3].

The second issue involves the long term data. There are two important must emerge in the simulation. First there is a relationship between long ter arousal that must be modelled. In the simulation this is simply a matter of cl final connection strength between cell assemblies for the various runs. Seco must be strong enough when arousal is high that recall is possible even wher passes that STCS dissipates.

All of the necessary significant trends can be found in the data shown Reminiscence can be clearly seen by examining the minimum recall interval. recall was tested at shorter time intervals but was not possible. What is signi these results is that, in the MultiTRACE2 model, this improvement in perforn come as the result of further learning since learning is completed during the period, but from the dynamics due to the temporal characteristics of cell ass residual fatigue and short term connection strength. Further, the relationshi arousal and short term recall can also be clearly seen as the minimum recall t by more than a minute and a half from when arousal is low to when it is at it

Table 6.1. Kleinsmith paradigm simulations

Parameter	Interpretation	Value
σ	short term connection strength gain	0.3
ρ^+	excitatory input resistance	5
ρ^-	inhibitory input resistance	2
γ	external control	0.5
ε	learning rate	0.2
τ	fatigue threshold	0.7
π	fatigue power	3

Arousal	Minimum Recall Interval	Long Term Recall?	Final Strength
0.55	80	NO	.123
0.60	90	NO	.156
0.65	100	NO	.187
0.70	110	NO	.215
0.75	120	NO	.250
0.80	125	NO	.270
0.85	135	NO	.300
0.90	145	NO	.326
0.95	150	YES	.473
1.00	155	YES	.485

The leftmost column gives the value of arousal for the simulation run. Recall Interval column shows the minimum length of time (in seconds before recall will occur in a Kleinsmith-paradigm test. The Long Term shows the result when learning is on and recall is tested after the simu (corresponding to the passage of a long period of time). The Final Str the learned connection strength from the first to the second element. discussed in the section on the learning rule. For explanations of the (Sonntag, 1991).

The long term trends can also be clearly found in the simulation result recall is not possible except when arousal is nearly at its maximum level. Fu strength of learning increases as arousal does. It is worth noting that the rel between arousal and the final connection strength is not linear; there is a sig increase in the learning rate when arousal becomes larger than 0.90. This is change in connection strength is strongly mediated by fatigue; the result of small changes in the amount of fatigue generated (at very high levels), can ha large impact on learning. The implications of this will be discussed in the ne

A point which should not be lost is that this data has not been simulate successfully (nor even accounted for theoretically) in the 30 years since the I results were first published. Since the successful simulation of the Kleinsmit credence to the TRACE model of learning it is possible to use this theory to se results have proved troublesome. While factors such as arousal and short te strength were necessary in modeling the Kleinsmith results they have been u previous, unsuccessful, models. The new factor which allows TRACE (and MultiTRACE2) to model this data is fatigue; and, in hindsight, it is relatively why fatigue has not been included in previous models. For symbolic models be virtually meaningless if not contrary to the symbolic paradigm of universa Connectionist models, on the other hand, have shied away from fatigue both lack of strong physiological evidence (now changing rapidly) and because th connectionist models have been atemporal. However, as will be discussed in section, the impact of fatigue on learning may go far beyond the modeling of Kleinsmith data, possibly providing a natural way of accounting for other dif results as well.

A note about the parameter settings. The length of the minimum recall be stretched by varying factors such as the fatigue rate, and perhaps more ir strength of inter-unit STCS. This particular set of simulation results was cho the recall interval is centered at exactly two minutes, when arousal is at its m (which was the target behavior). Ignoring all other factors, recall is not poss two minutes with these settings unless arousal is low at presentation time. Ir "true" parameters are probably somewhat different. An artifact of the simula environment is that the subject is never distracted, always gets the input pre etc. Some other the factors which may account for some of the variation in t results have already been discussed, such as the pattern of connections, initi strength between units and arousal at recall time. While all of these factors n the results slightly, the basic trends will still hold. The essence of the Kleinsı are the short versus long term trends, not the exact rates of recall.

Simulations were also run to test how the level of arousal at recall time recall interval (Figure 6.4). The differences found suggest that arousal level could be a significant factor in the probability of remembering. Again it mus however, that while a similar input pattern will most likely generate a similar arousal the next time it is experienced, this does not mean that this should b level during the recall test. This is because the perception of the input (thro activation of the appropriate cell assembly) is what triggers the change in ar Therefore the arousal level would not change until after recall had occurred.

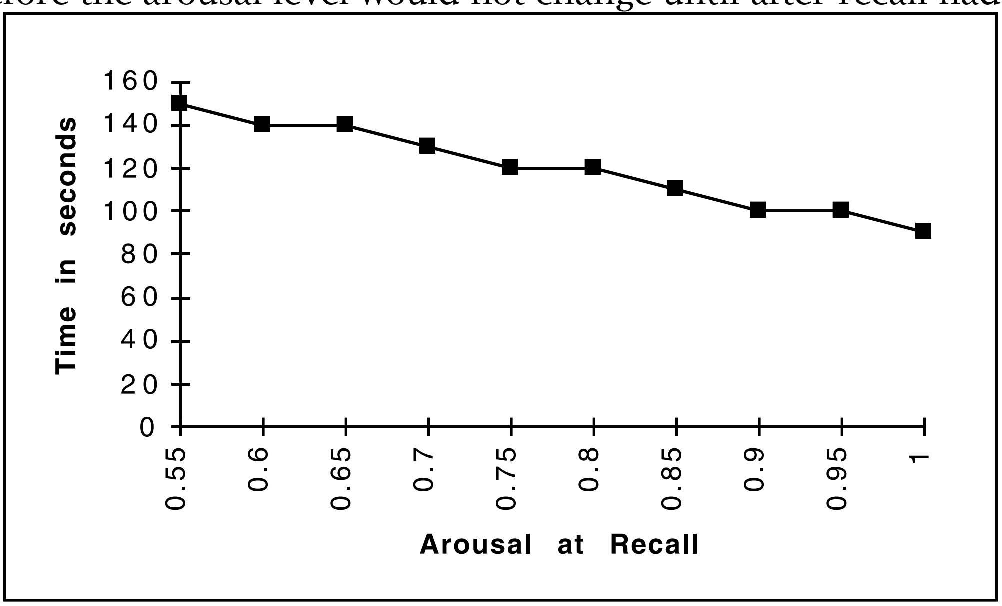

Figure 6.4: Effect of Arousal Level on Recall. This graph was generated using procedure as for Table 6.1 with the only difference being that the level of arc time was varied. In all cases the level of arousal at presentation was set to 0.

Another interesting aspect of the simulation results is that they make a prediction. The earliest test interval in the Kleinsmith paradigm has always b minutes. With MultiTRACE2, however, it is a simple matter to test even short What the results show is that at these shorter intervals recall is poor even wh low, which is contrary to the original predictions of Kleinsmith and Kaplan. for this effect is fatigue. Even using the revised TRACE equations fatigue rem dominant factor in causing a cell assembly to shut down whether arousal is l This means that even when arousal is low, cell assemblies will generate enoug have a temporary effect on recall. Immediate recall, during the first several s still be high since the cell assemblies will be consolidating, but then will quic What these simulations still do not accurately measure is how much of an eff and other forms of local inhibition will have.

Credit assignment and fatigue

The major difference between credit assignment as it is manifested in th dissertation and as it is presented in other models, and particularly Grossbe Sutton's, is in the incorporation of fatigue. Fatigue is crucial to the success o from a number of perspectives. The focus so far has been that fatigue provid SESAME architecture with an explanation for a number of issues that are othe easily resolved. Chief among them with regard to this dissertation are the Kl paradigm data and the problem of the direction of sequence in associative m of these cases fatigue affords a clean, system compatible, explanation of prob otherwise have proved difficult to model. Further, fatigue provides a way of credit assignment model within the same framework.

Fatigue makes credit assignment far more selective than in a model bas association. Part of the appeal of Hebb's original learning rule is its simplicit that all learning comes as the result of the correlation of neural firings. The fatigue into the learning rule allows for a far more sophisticated type of corre while keeping the rule relatively simple. The brain has been called a "coincid and in fact that is how the Hebb rule works, by detecting the coincidence of firing simultaneously. The inclusion of fatigue into the learning rule, howev creates a stricter criterion for coincidence. It is not enough for a neuron to f so repeatedly. The repetition of firing needed to generate fatigue means that will only occur when a cell assembly is active either repeatedly or with unusu

The fatigue-learning linkage may also help to explain other learning dat modelled in this dissertation, such as the difference in learning rates betweer learning. This is because, as Hebb first postulated in *The Organization of Behavior* (1949), in unfamiliar domains (or, in the case of young children, when all do unfamiliar) there will not be well learned cell assemblies, nor strong connecti cell assemblies. The effects of this lack of structure are twofold. First, a cell without strong internal connections will not be able to sustain reverberation. reverberatory activity will mean that such cell assemblies will tend to become before there is a buildup of fatigue. Second, the fact that the average intensi within a cell assembly will be lessened, combined with the fact that there will weak connections between cell assemblies means that cell assemblies will not activating each other. In an organism where there are other structures availa corresponding to other domains, this will have the effect of making the orgar distracted because such domains will tend to easily dominate the new, unstru domain. In an organism without well formed structures, organisms will effec sensory dominated because direct environmental input will be required to ac assemblies. Even when an organism avoids distraction (one of the functions inhibition) and manages to concentrate on the new domain, the limited abilit activity will negatively impact learning. As structure is built up the ability to will increase, with a corresponding increase in fatigue, and the speed of learn quicken.

The incorporation of fatigue into the learning rule places a premium on the molecular level. At this level repetition comes in the form of pairs of neu synchrony, and is required to generate the fatigue that activates the learning cases where repetition is high, such as when arousal is high, learning will be strong. At the behavioral level repetition is required to build up the neural s enable repetition at the molecular level. This emphasis on repetition ensures coincidences detected by the brain through its learning rule are significant. exists the capability, through the arousal system, to circumvent the need for repetition by allowing for intense repetition at the molecular level within a si

At the cellular level fatigue also provides a framework for understandin learning process. Fatigue comes as the result of a neuron continually firing a transmitter substances to other neurons. The depletion of the neuron's ener the system has not efficiently allocated its resources. Learning can be viewed to this allocation problem. In Hebb's rule neuron X is channeling transmitte which in turn release it to fire neuron Y. If it is not doing it well enough to m demand then a reasonable change would be to increase X's ability to enable t From a mechanical point of view, fatigue might be critical to the physical pro learning as well. Just as the waste products of muscle usage, such as lactic a cleanup appear to be central to the process of building muscles, it may well b some aspect of neural fatigue is critical to triggering the learning process.

In summary, far from being a necessary but unfortunate part of a syste of neurons, fatigue appears to serve a number of important functions with re assignment and learning beyond its role as a shutoff mechanism for cell asse activity. Among these are:

1) Fatigue may provide the trigger necessary to begin the synaptic cha involved in learning.

2) A learning rule based upon fatigue places a premium on molecular : ensuring that the associations made through the learning process are signific

3) Fatigue solves the problem of temporal coding in associative learnir

4) Fatigue can play a protective role in new learning. In situations of l learning is so strong that were it not for fatigue, rehearsal and reflection wou form new, potentially spurious, connections.

Fatigue has negative connotations because it implies an inability to perf functioning. While this may be true on occasion, the shutoff function may be normal functioning of an organism. A strongly active cell assembly which dc could stay active indefinitely. Further, given the learning problems that fati help solve it would appear that evolution has enabled the brain to take advai physical properties.

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[1]STCS provides a good example for how theoretical changes are ma the SESAME research group. The SESAME position, based upon some early re neurophysiology, has always been that STCS is non-specific and hence this w version that Sonntag adopted in his dissertation. After extended experiment it became clear to me that there were numerous advantages to the specific ve proposed in this dissertation. I proposed the change in a SESAME meeting be any neurophysiological evidence. I outlined my reasons as I do in this chapt implications of both versions were discussed at length. The group came to tv conclusions: First, that the design of the neurophysiological experiments tha original position were not compelling enough to provide convincing evidence position. Second, the theoretical arguments were so compelling that for the until more neurophysiological evidence becomes available, we would adopt t position.

[2]This might seem contrary to one of the themes of this dissertatior that information is not treated neutrally. With such an interpretation one wc if an input generated a particular level of arousal after one presentation it sh similar level at the next presentation. However, there is a lag between the tin and the time that arousal begins to affect processing, the input must activate system which must in turn release dopamine or whatever neural transmitters and this lag is likely to be longer than the 50 to 100 milliseconds that the act

assembly requires. Further, when the cell assembly is activated by an intern
the case in the recall test, the change in arousal can only come as the result o
assembly's activation and therefore must necessarily come later.

[3]Inhibition could also provide the kind of short term negative imp
activity necessary. However, this is extremely unlikely for two reasons. Firs
inhibition as the primary factor in the Kleinsmith results has been extensivel
rejected as was reviewed in Chapter 3. Second, as was shown in Chapter 5, l
inhibition, which would be the only type of inhibition capable of such an im
from particular configurations of active cell assemblies, not from general sys
and therefore is not predictable with regard to system variables such as arou

CHAPTER 7

CONCLUSION

The starting point of work on this dissertation was an miscellaneous co consolidation data which apparently had little to offer learning theory. Thes that there is a short period of time, the consolidation period, during which le becomes permanent. A careful examination of the data, however, shows that is not, as is often hypothesized, merely a byproduct of the physical process o Rather, it is integral to many of the core issues of learning theory such as wh and how strong the learning is. The main vehicle for studying consolidation dissertation and for showing what a consolidation-based model is capable of model. TRACE models the time course of activity of a cell assembly, a neural representation of an object (whether concrete or abstract). It also provides f consolidation through the action of its learning rule, a rule which hypothesiz a relationship between learning and correlated neural activity. Such a rule d the learning of information and the processing of information through the m consolidation. The power of a consolidation-based model of learning, such a comes in the ability of the cognitive architecture as a whole, in this case the S architecture, to adjust the basic consolidation heuristic according to the situa arrangement which requires that the architecture have built in sensitivities to situations.

In making the case for a consolidation-based model of learning this dis had to address several key questions. First, is the question of what consolid dissertation has taken the somewhat unusual point of view (from the perspec consolidation theory, not from a physiological point of view) that consolidati process related to correlated neural firing. Next are two related questions. I question of what is gained by having an active model of consolidation. Next, question of how a learning rule based upon correlated neural firing can be sc address issues of behavioral data. The TRACE model allows both of these qu answered by providing a molar level simulation of molecular level events. Si models the aggregate behavior of neurons it is ideal for scaling their behavio behavioral level. In turn this allows consolidation to be studied at the same l

One of the major tests of any model is what data it can account for. In dissertation there are two major sources of data: the consolidation data and paradigm reminiscence data. The simulations of these data are critical to the dissertation and lay the foundation for extending the consolidation discussio general realm of learning theory and even into the topic of large-scale simula

Consolidation

This dissertation makes the claim that consolidation is a fundamental n learning. The arguments and data in Chapter 2 show that there is much mor consolidation than a simple process which makes learning permanent. Empi a large body of such consolidation data that a learning theory must address. into two basic categories: events that negatively impact learning, and events learning. This dissertation takes the point of view that these events are syste coherent, and are the result of an active consolidation process. Further, the learning system is able to take advantage of these influences in becoming sen variety of domain independent factors.

The construct through which consolidation is implemented is the cell a modelled in a simulation called TRACE. A cell assembly is a collection of neu because of their strong interconnections, tends to behave as a unit, thereby s kind of connectionist "symbol." The cell assembly is a natural method for ex consolidation because cell assembly theory postulates perception as an active similar time course to consolidation, and the activity of cell assemblies is sub same sorts of influences as is consolidation. Further, the activity of the neur cell assembly provide a mechanism for a consolidation-based learning systen correlation between the activity of a cell assembly and learning is where the c connection is made between learning and processing. Understanding the co with a simulation like TRACE, therefore, involves showing how TRACE is capa automatically adjusting the activity of cell assemblies according to the situati described by the data. Simply modelling the data is not enough, however; it important to show that a consolidation-based approach to learning provides purpose, coherent solution to learning problems such as credit assignment.

The solution afforded by the TRACE model is actually quite simple in co elegant in application. The basis for all learning in TRACE is contiguity, whet molar or a molecular level. The essential contiguity heuristic is that things th to each other in time are probably related, whether "things" means events or neurons. A general purpose learning system, such as the one humans have, however, be more sophisticated than this. Much of the power of the system ability to make adjustments to the basic contiguity rules. This ability stems f sources, including the results of previous learning, the specification of the le and architectural factors. These sources of adjustment impact the consolidat direct and straightforward ways, providing an approximate measure of the re importance of the current situation.

The mechanism through which these adjustments are made is neural ac through its function as the basis for the learning rule. This activity, mediate of cell assemblies, has two dimensions, intensity and duration, each of which have distinct impact on the learning process. Duration serves as the basis fo contiguity. As a cell assembly stays active other cell assemblies also become therefore, their neural firing becomes contiguous with that of the original ce an architecture based upon cell assemblies cognitive structure consists of linl units. Duration is critical in the process of building these linkages through it enabling correlated neural firing between representations. When two cell ass correlated neural firing the connections between them tend to be strengthen assignment terms this essentially answers the question "what leads to what?" consolidation hypothesis, therefore, answers this question by using a relativ method of extracting sequential dependencies. This is as opposed to underta complex and unpredictable task of attempting the analysis of situations that approaches tend to favor.

Factors which impact duration include inhibition and fatigue. Inhibitic impacts duration in situations where the activation of one concept precludes activity of another. The most straightforward example of this would be a pe competition. Such competition results in a number of cell assemblies which otherwise be activated as the result of an input, instead becoming suppresse the other hand, is a self-limiting factor. In terms of duration what fatigue dc kind of cap on how long a cell assembly can stay active. Fatigue is instrumer the basic consolidation heuristic, the five second rule, since it is the primary responsible for the shutdown of activity within a cell assembly.

Several factors also influence duration in an enabling capacity. The mc of these is input which, in most cases, is necessary for the activation of a cell Input alone may not be enough to bring reverberation however, and this pot shortcoming is the basis for the short term connection strength mechanism. connection strength provides a cell assembly with temporary connections wh to compensate for a lack of strong internal connection strength, thereby enal weakly connected cell assembly to reverberate when the input is sufficient.

Intensity is probably more important to molecular level contiguity than
This molecular level contiguity serves as the basis for the ability to make adju
strength of learning, addressing the credit assignment issue of how much inf
factor has on another. It has been hypothesized in this dissertation that adju
strength come as the result of increasing the firing rate of neurons. This inc
because learning is tied directly to neural firing. By adjusting strength throu
rather than duration, side effects involving the consolidation five second heu
avoided.

The issue of how strong to make a connection is most closely related to
is also impacted by inhibition. The hypothesis in this dissertation is that the
an organism directly reflects the perceived importance of the situation the or
Factors such as pleasure and pain which directly bear on an organism's well
strongly related to its arousal level. It is imperative, therefore, that the organ
sensitive to situations which not only are directly pleasurable or painful, but
could potentially lead to pleasure or pain. It is this sensitivity which allows a
learn differentially depending upon the importance of a situation. Conversel
plays only a peripheral role in the determination of the intensity level of a ce
is more often the case that inhibition's role is the prevention rather than the
activity of a specific cell assembly.

The simulation experiments in Chapter 5 were designed to show that th
model is capable of behaving appropriately in the framework just described.
1 through 4 each examined some facet of the TRACE model (or TRACE as emb
the SESAME framework) and either showed that TRACE was already capable c
in the specified fashion or could be modified to do so. Further, the modifica
TRACE model were not made arbitrarily, but rather were done systematically
with existing theory and using neurophsyiological constraints where possibl
method of model extension is part of the SESAME philosophy of the "systema

exploitation of failure" in which systems are kept as simple as possible and a modified when a further understanding of the underlying theory requires it. success of such a philosophy is that the modifications to the model remain tr original specifications.

The extension of TRACE to include an arousal component is an excellen of how this method works. While the role of arousal had already been specif SESAME architecture, it had not been implemented in TRACE. TRACE, as orig specified, modelled the activity of a cell assembly under "ideal" conditions; tl simplification in this case being that "non-ideal" conditions were not conside those non-ideal conditions are lowered levels of arousal. By adding arousal t model its scope was extended to a larger set of data. Further, and crucial to is the fact that the new model is able to behave in exactly the same fashion as when arousal is set to its maximum value. In this case, therefore, the model extended without any disturbance to the original theory. This was not the ca the changes, such as with the reimplementation of fatigue, but in such cases taken to ensure that any changes improved the model without forfeiting prev results. In the case of fatigue, on the other hand, close examination revealed fatigue in the original theory was too comprehensive, necessitating a change

On the whole the TRACE model proved to be capable of fulfilling all of i theoretical roles with regard to the duration and intensity of activity. The im input and STCS factors were limited strictly to an enabling capacity. The maj arousal, conversely, was on the intensity of activity. The major impact of fat conjunction with inhibition, is on duration. Finally, LTCS impacted both din this point in the study of consolidation it is probably too early to speculate to whether or not this dual impact is "correct". I have collected a series of reas why LTCS should and should not have various effects on consolidation, but l

able to come up with anything definitive as yet. Nevertheless, this is an impo
future work that needs further development.

Reminiscence

The consolidation framework just described provides an attractive lear
However, while this framework is appealing for many reasons, including tho
in the introduction, as well as for the coherence and flexibility it affords, the
evidence on its own is not a compelling reason to assume that the cell assemb
learning embodied in TRACE is accurate. There are, after all, other models o
consolidation, most of which bear little resemblance to the one described in t
dissertation. The crucial evidence necessary to lend this model credence ove
provided by the Kleinsmith paradigm reminiscence data.

Even 30 years later the Kleinsmith results appear to be an anomaly whi
explanation; worse, the results do not even make sense when viewed from a
perspective. However, by placing the results in the context of consolidation
them using the framework developed in this dissertation, they not only appe
but actually are sensible, even from an adaptive perspective.

The anomalous nature of the results stems from the high arousal cond
is not obvious what might account for the poor performance found in the sh
condition. Second, this poor performance does not appear to make sense ad
should an organism be prone to forget important events in the short term?

The answer to the first problem is clear in light of the simulations run i
dissertation: fatigue stemming from the intense activity associated with high
the pertinent cell assemblies relatively inaccessible in the short term. The an
second problem requires thinking about the situation in terms of the framew
the previous section. In that section is was hypothesized that one of the imp
fatigue is in regulating the duration of activity. In situations of high arousal

becomes all the more critical. When high arousal is triggered the active cell a become intensely active and therefore learning is strong. The high arousal ir this is an appropriate time to "turn up" learning because something importai happened. In such a case learning is essentially optimized.

It might seem that allowing the simple reactivation of the pertinent cell would further enhance the situation since it means that learning for the even and that forgetting would not be a problem. This, however, has two potenti First the learning could become so strong as to essentially hardwire the learn thereby not allowing for future variations. Second, since other cell assembli active at the later time, they too will form connections to the cell assemblies i Given that learning can be effectively optimized when the events initially occ reason to risk contaminating the results. Further, the inability to recall some imply the inability to process it. The MultiTRACE simulation results showed the cell assemblies in question could not be activated internally (by other cel they could still be activated by direct input.

The Kleinsmith simulations accomplish several objectives: They firmly the active relationship between processing and learning. They add considera the TRACE model of learning since no other model can satisfactorily account effects. Finally, they lend further credibility to the original experiments ther though they have been replicated many times, have been attacked as not bei meaningful.

Learning

The focus of this dissertation has been on the consolidation data, how model can account for it, and why it appears to be a powerful framework for Because the onus was on showing the plausibility of such a model, considera was spent on what the model might reveal about learning generally. Some o will be addressed in the future work section, but one which is not, and whicl examining more closely is the relationship between learning and affect.

Classical treatments of cognition treat affect as its own little box separa of the rest of cognition. This separation is especially clear in popular science often portrays intelligent robots as being devoid of emotions. The point of v this dissertation is directly contrary to those positions. The basic five seconc heuristic is fairly powerful on its own, but it pales in its power compared to a equipped with an arousal mechanism. The arousal mechanism makes learnir rather than treating every situation equally, arousal gives the organism the a automatically respond to the importance of events based either upon their in potential consequences. Further, the arousal system does not require ration determine this importance, but it arises naturally from the construction of th Far from being an unfortunate artifact of cognition, viewed from this perspe one of the central ways of making cognition more efficient.

Simulations

One of the great problems in simulating psychological data is dealing w widely held perception that simulations are "doomed to succeed." This is esp for a model such as TRACE which contains a large number of parameters anc When choosing an isolated behavior it would be relatively simply to modify T model the behavior by changing any of a number of parameters. Simulation rightfully criticized for not proving anything because with enough paramete to model anything. The SESAME position is that nature, through evolution, c operate by adding a new mechanism and therefore a new parameter or varia new behavior, but rather that it is far more adaptive to have fewer, more ger mechanisms. With such a philosophy, therefore, new parameters and variab added sparingly, even grudgingly. Such a policy has several important impl

change must come through failure; variables should be added only when th
incarnation of the model proves inadequate. Second, changes must be stron
theoretically; it is not enough that the model is inadequate to deal with new
important to understand why, and how a new component can address the sh
Finally, the new changes cannot undermine the good results already obtaine
do so the previous theory must be re-examined and changed.

With these policies in place proper management of a model can ensure
simulations are meaningful. In the TRACE model, for example, each variable
parameter has a well specified theoretical role. With such a framework it is n
to change a setting or equation arbitrarily without a thorough examination o
a careful study of the implications of such a change. While this can make sin
data more challenging it also provides a framework for understanding which
changes in the model should take. In attempting to model the Kleinsmith re
example, I found the previous instantiation of TRACE to be inadequate. The
the lack of differentiation in fatigue in cases of high and low arousal. By exa
data in the light of the role of fatigue in TRACE, it was possible to make the c
between the fact that fatigue was too high when arousal was low and the fact
was the only mechanism available for shutting off activity in TRACE. The ori
specification of the role of fatigue was too general - that fatigue should alway
active cell assemblies - and the new data helped to narrow and focus the the
the changes in a model like TRACE come in the same fashion - new data shar
previously overgeneralized theories. This is in marked contrast to models wh
add variables and parameters arbitrarily.

Of course variables and parameters do get added to the TRACE model,
was in this dissertation. This may be somewhat misleading, however, since t
between arousal and cell assemblies was postulated as a possible explanation
Kleinsmith results when they were originally published. Further, arousal wa

original TRACE equations but was held constant with the key tenant that the assumed "ideal conditions." Indeed with arousal set at its maximum level th remain the same today. Therefore the original TRACE equations contained a simplification, that arousal be held constant. This simplification was useful i that there was one less factor to manage. Once the original simulation was in state, an easier job without the need to consider arousal, then arousal could was in this dissertation. Furthermore, even as this policy facilitated the origi development of the model it also meant that arousal could be further studied understood before it was added.

The SESAME research group takes this form of model management one further with a limited form of peer review for major changes in its various m this is a helpful process where members of the group can receive suggestions on their work, and in part this is born of necessity since changes in one part architecture can impact other parts of the architecture and therefore other n The end result of this process is that far from simulations in SESAME being "c succeed" even many of the successes are rejected because they do not meet a necessary requirements. A solution where arousal directly generates fatigue would account for the Kleinsmith results, but would not make sense from a t point of view, nor would it appear to be in accord with neuophysiological da therefore it would not be an acceptable change to the SESAME architecture.

Future work

Though there are numerous directions that this research could take, tw seem particularly appealing. The first is very much in accord with the theore established here and would continue the generic treatment of learning but at higher level. The second is more empirical and would involve further specifi learning rule in order to directly model more data. Further down the road p include studying how consolidation works in building hierarchy or the imple MultiTRACE-style model on a real task.

Generic learning

One of the themes in this dissertation has been that the learning systen to certain generic events. This emphasis on the generic rather than the speci because of the complexity of the world and the fact that in new domains ther theory to fall back on. So far the development of this treatment has been lar; Chapter 5 went through a variety of simple situations and showed how the s; respond. While it was shown that TRACE is capable of behaving in the requi no large scale simulations were run to show that the system as a whole is cap behaving in such a way. With MultiTRACE, however, such simulations are be possible and one of the important next steps in showing the viability and pov consolidation construct is creating these generic simulations to show the bro consolidation within SESAME.

In an unpublished manuscript, Booker and Kaplan (1989) describe fou generic events to which humans appear to be particularly sensitive. They cal importance, environmental impact, match/mismatch and reward. These fou make an excellent starting point in a treatment of generic learning processes. Match/mismatch, for example, was briefly described in Chapter 5 in terms of confusion. A match is a clarity situation where the organism's prediction of happen next has come true. Because the internal model supports the same s environment, activity is intense and focused. By contrast, when the organisı is wrong, the internal model supports a different structure than the environr result is weak, diffuse activity. Each of these states should be recognizable tl and confusion detectors which in turn should feed into the arousal system. . test this might start by training a system to learn an internal model. The ne>

to start it in accordance with the model, but then to deviate from the learned important way. For example, the model could be trained to learn various sec test of confusion would involve starting with a well learned sequence but fini sequence with a novel outcome.

The pattern of connections is also important in understanding the envi impact heuristic which is sometimes known as the "last thing" principle. The hypothesis is that this heuristic arises due to a pair or important properties c architecture. The first property is that similar things are processed near to e brain. This property is important in a number of ways, including providing perceptual competition. The second property is closely related to such comp reflects the fact that the closer two processes in the brain are to each other, t interference will result (Kinsbourne, 1982). This interference probably com of a combination of regional inhibition and increased local inhibition througl Taken together these two properties have the result that when working withi there will tend to be a relatively high degree of interference because most of will take place in a small area of the brain. However, when switching to a ne locus of activity will shift away and the last few things from the first domain receive as much interference and therefore will tend to be better learned.

Importance has already been discussed in this dissertation in some det Importance can be learned, such as when making an association between an pleasure or pain, or it can be innate, such as a fascination with snakes. In th the emphasis has been on the linkage between importance and arousal.

Reward is probably the most highly studied of these heuristics, servin for a number of learning theories. In the SESAME framework, the enhanced associated with reward comes as the result of the high level of arousal genera pleasure and pain. Simulations showing how rewards are backward chained similar to the bucket brigade will probably be critical in establishing consolid

credit assignment method. In this framework, affect, be it positive or negati
traditional evaluation functions used in much of machine learning. Because
emphasis on rationality in cognitive science and artificial intelligence it woulc
useful to show that a credit assignment system based upon affect is capable c
least as effectively as those based upon evaluation functions.

Creating simulations that show each of these effects is important in a n
respects. First, it would show that although the learning rule is based upon
principle - correlated neural activity - it is extremely flexible and powerful in
context of a cognitive architecture. Second, it would serve as the basis for m
wider variety of results and therefore provide further data for specifying anc
theory. And finally, it provides a relatively new way of examining learning b
molecular level effects up to the behavioral level.

The learning rule revisited

A number of changes to the basic Hebbian learning rule were made in t
dissertation; for example, the inclusion of fatigue was discussed in some det
previous chapter. A further change which was not emphasized as strongly w
learning rule in the SESAME framework is compensatory, that is that the stre
one connection will lead to the corresponding weakening of one or more oth
This change was not fully addressed in this dissertation because it is not dire
the data being modelled; however, in any full treatment of learning it will be
issue. This dissertation has focussed upon those factors which directly impa
assignment through consolidation and therefore the issue of the distribution
was not critical. However, this issue becomes much more relevant when taki
step.

In the process of trying to build generic models of key learning situatic
specification of the learning rule will be needed. Preliminary experiments ha

there are a number of issues which still need to be resolved including the spe how the compensatory rule is to be handled and how the learning rate shoul

In terms of the rate of learning this dissertation modified Hebb's basic include fatigue, correlating learning not only to activity, but to fatigue as wel rule developed in this dissertation proved quite successful in modelling the k but further experimentation has shown that more development is still neede that arises when dealing with sequences is how the timing rate of presentatio relative strength of association. It is possible, even probable, for example, th optimal time interval between two elements in a sequence. This is yet anothe the effect of fatigue, because in a system based strictly upon correlated activi time interval would be zero, since a time interval of zero would ensure the m correlation of activity between two cell assemblies. However, with a learning fatigue component this is no longer necessarily the case since learning does r strong until neurons are fatigued. With fatigue being such a strong factor, to learning from one cell assembly to another it is probably best for the time int the presentation of the two elements to be such that the first is somewhat fat time the second is presented. With such an arrangement the second will be r active while the first is in its learning period. There is empirical support for (Miller and Barnett, 1993), and while the optimal presentation interval appea according to modality (Posner, 1967) in general it appears to be on the orde second (Landauer, 1964). Initial tests on MultiTRACE as specified in this diss show that the optimal presentation interval would be closer to two seconds, indicating that the fatigue exponent used was too large.

Just as the post- versus pre-synaptic issue became crucial in the discus STCS in going from TRACE to MultiTRACE there is a similar issue which has y resolved with regard to the compensatory learning rule. In this case it is wh are input or output compensatory. The form of the rule becomes critical wh

situations such as multiple intersecting sequences. Other unresolved issues i
compensatory learning include what sort of reallocation algorithm should be
example, one strategy, called "reverse Robin Hood" takes connection strengt
weakest connections when strengthening a connection.

The fact that this dissertation has not directly addressed these issues ir
emphasis on learning is in accord with the SESAME simulation philosophy. T
rule used in this dissertation is sufficiently well specified to model the Kleins
it undoubtedly too simple to account for other data such as with multiple se
Nevertheless the results achieved in this dissertation lay a firm groundwork
study, providing not only a starting point, but also deeper insight into the is
surrounding consolidation; understanding the mechanisms underlying learr
step towards building a more complete theory.

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