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A Neural Network Approach to Hippocampal Function in Classical Conditioning

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Hippocampal participation in classical conditioning in terms of Grossberg's (1975) attentional theory is described. According to the present rendition of this theory, pairing of a conditioned stimulus (CS) with an unconditioned stimulus (US) causes both an association of the sensory representation of the CS with the US (conditioned reinforcement learning) and an association of the sensory representation of the CS with the drive representation of the US (incentive motivation learning). Sensory representations compete among themselves for a limited-capacity short-term memory (STM) that is reflected in a long-term memory storage. The STM regulation hypothesis, which proposes that the hippocampus controls incentive motivation, self-excitation, and competition among sensory representations thereby regulating the contents of a limited capacity STM, is introduced. Under the STM regulation hypothesis, nodes and connections in Grossberg's neural network are mapped onto regional hippocampal–cerebellar circuits. The resulting neural model provides (a) a framework for understanding the dynamics of information processing and storage in the hippocampus and cerebellum during classical conditioning of the rabbit's nictitating membrane, (b) principles for understanding the effect of different hippocampal manipulations on classical conditioning, and (c) numerous novel and testable predictions.

The neurophysiological basis of classical conditioning of the rabbit's nictitating membrane (NM) has been the subject of numerous studies in the past decades. Briefly, these studies show that (a) acquisition of classical conditioning is still possible after hippocampal lesions (Schmaltz & Theios, 1972) but not after lesions of cerebellar regions (Thompson, 1986), (b) hippocampal lesions impair more complex conditioning paradigms (Solomon & Moore, 1975), (c) some hippocampal synapses show long-term potentiation (LTP) during acquisition of classical conditioning (Weisz, Clark, & Thompson, 1984), (d) the acquisition of some classical conditioning paradigms can be facilitated by inducing LTP in the hippocampus (Berger, 1984), (e) the activity of pyramidal cells in the hippocampus reflects the temporal topography of rabbit NM responses (Berger & Thompson, 1978b), and (f) this neural activity depends on the integrity of cerebellar circuits (Clark, McCormick, Lavond, & Thompson, 1984). These results pose some intriguing questions about hippocampal participation in classical conditioning: (a) Why do hippocampal lesions seem to affect some but not other classical conditioning paradigms, (b) What is the functional meaning of hippocampal LTP, (c) What is the functional meaning of the behavior-related hippocampal neural activity, and (d) What are the functional interactions between hippocampus and cerebellum during classical conditioning?

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In an attempt to address some of the questions about hippocampal involvement in classical conditioning, various attentional models of hippocampal function have been proposed. Although different authors had proposed that the hippocampus participates in attentional processes (see Schmajuk, 1985, for a review), it was not until recently that attentional theories of the hippocampus received a mathematical treatment that allowed them to generate accurate descriptions of hippocampal function. The first attempt to generate a precise attentional theory of hippocampal function was submitted by Moore and Stickney (MS; 1980, 1982), in which they described classical conditioning of the rabbit NM response in a rendering of the Mackintosh (1975) attentional model. The MS model incorporates an attentional rule that "tunes in" relevant conditioned stimuli (CSs) and "tunes out" irrelevant CSs. When tuned in, a CS increases the rate at which it changes its associations with the unconditioned stimulus (US). When tuned out, a CS decreases the rate at which it changes its associations with the US. Moore and Stickney (1980) proposed that hippocampal lesions prevent poor predictors from being tuned out. Under the tuning-out hypothesis, the MS model correctly described the effects of hippocampal lesions in blocking and latent inhibition.

Schmajuk and Moore (1985, 1989) studied the effects of various hippocampal manipulations on the classically conditioned NM response in an elaborated rendering of the Moore and Stickney (1980) model called the MSS model. Under the tuning-out hypothesis suggested by Moore and Stickney (1980), the MSS model correctly describes the experimental effects of hippocampal lesions on delay conditioning, conditioning under optimal interstimulus interval (ISI), conditioned inhibition, extinction, latent inhibition, blocking, and mutual overshadowing. The model, however, is inconsistent with experimental findings describing the effects of hippocampal lesions on trace conditioning with shock as the US

under short and long ISIs, trace conditioning with airpuff as the US under long ISIs, discrimination reversal, and sensory preconditioning. Schmajuk (1986) suggested that long-term potentiation facilitates the tuning in of good predictors. Under the tuning-in hypothesis the MSS model is unable to describe the effects of hippocampal induction of long-term potentiation in the acquisition of classical discrimination. Under the assumption that hippocampal neuronal activity is proportional to the magnitude of CS–US associations, the MSS model describes hippocampal neuronal activity during acquisition and extinction of classical conditioning.

A second computational attentional model of hippocampal function was proposed by Schmajuk (1984) in which he described the effect of hippocampal lesions in terms of Pearce and Hall's (PH; 1980) attentional model. According to the PH model, when a CS is followed by a US, a CS–US association (a prediction of the US by the CS) is formed. Changes in CS–US associations are controlled by the absolute difference between the US intensity and the "aggregate prediction" of the US, computed on all CSs present at a given time. When the actual and predicted US are equal, no changes occur in CS–US associations. Schmajuk (1984) hypothesized that the hippocampus computes the aggregate prediction used to control CS–US associations.

Schmajuk (1986, 1989; Schmajuk & Moore, 1985, 1988) introduced a real-time version of Pearce and Hall's (1980) attentional model, designated the SPH model. Hippocampal lesions imply impairments in the computation of the aggregate prediction. Under the aggregate prediction hypothesis, the SPH model correctly describes the effect of hippocampal lesions on delay conditioning, conditioning with short, optimal, and long ISI with a shock as US, conditioning with long ISI and airpuff as the US, extinction, latent inhibition, generalization, blocking, overshadowing, discrimination reversal, and sensory preconditioning. However, under the aggregate prediction hypothesis, the SPH model has difficulty describing the effect of hippocampal lesions on conditioned inhibition and mutual overshadowing. The aggregate prediction hypothesis assumes that LTP induction increases the integration of multiple predictions into the aggregate prediction by way of increasing CS–CS associations. Under the aggregate prediction hypothesis, the SPH model has difficulty describing the effects of LTP on discrimination acquisition. The aggregate prediction hypothesis assumes that neural activity in the hippocampus is proportional to the instantaneous value of the aggregate prediction. Under the aggregate prediction hypothesis, the SPH model correctly describes neural activity in hippocampus during acquisition but not during extinction of delay conditioning. Recently, Schmajuk (1990) applied the SPH model to the description of the effects of hippocampal lesions in temporal discrimination and spatial learning.

Although both the MSS and the SPH models describe the effects of hippocampal manipulations in many classical conditioning paradigms, neither one has been implemented as a neural network. This limitation is particularly important because a neural architecture is necessary for the design of a model that can be mapped onto the brain and hippocampal circuitry. Such a model would be able to close the gap between neuroanatomical structure and behavioral function.

In contrast to both the MSS and SPH models, Grossberg (1975; Grossberg & Levine, 1987) proposed an attentional neural network that describes classical conditioning. Given the relative success of the MSS and SPH models, it seemed reasonable to assume that when circuits that modulate attention in Grossberg's (1975) model are related to hippocampal function, then the model would be able to describe the effects of different hippocampal manipulations on classical conditioning. In addition, given the neural architecture of the model, we assumed that the model would provide clues regarding the functional anatomy of hippocampal circuitry.

Therefore, the present study contrasts experimental results regarding hippocampal manipulations in classical conditioning with computer simulations using a modified version of Grossberg's (1975) attentional model under an attentional hypothesis of hippocampal function. Typical hippocampal manipulations include hippocampal lesions (HL), induction of hippocampal LTP, and blockade of hippocampal LTP. The present article elaborates and extends the results presented in a previous article (Schmajuk & DiCarlo, 1990).

Neurobiological Constraints

This section reviews neurophysiological and anatomical data to establish the constraints for a neural model of hippocampal function based on Grossberg's (1975) attentional model.

Intrinsic Hippocampal Circuit

The hippocampal circuit can be divided in four regions: the entorhinal area, the subicular complex, fields CA1 to CA3, and the dentate gyrus. The "trisynaptic circuit" begins in the entorhinal cortex neurons, which project their axons to the dentate gyrus through the perforant path. In the dentate gyrus, the granule cells send their axons (mossy fibers) to the pyramidal cells in the CA3 field. In addition to the mossy fibers, the CA3 region receives a direct input from the perforant path. The CA3 pyramids send information to the CA1 pyramids through the Schaffer collateral system. In addition to Shaffer collaterals, the CA1 region also receives a direct input from the perforant path. The CA3 axons go (through the fimbria) to the lateral septal region, and the CA1 axons go (through the alveus) to the subiculum and entorhinal area. This last projection "closes" the trisynaptic circuit. Local circuits also play an important role: Recurrent collaterals from pyramidal cells excite basket cells, which in turn mediate a powerful inhibition of pyramidal cells.

For a relatively long time, it was assumed that the interconnections between the different hippocampal fields were organized in "lamellas" transverse to the rostrocaudal axis of the hippocampus (Andersen, Bliss, & Skrede, 1971). Recently, however, Squire, Shimamura, and Amaral (1989) and Amaral and Witter (1989) suggested that hippocampal organization is three-dimensional, a notion that differs sharply

from the classical view that regards the hippocampus as a series of isolated lamellas.

As reviewed by Squire et al. (1989), the entorhinal cortex receives inputs mainly from the parahippocampal and perirhinal cortical regions, the temporal gyrus, the insular cortex, the orbitofrontal cortex, and the retrosplenial region of the cingulate cortex. Each of these regions receives inputs from several unimodal and polymodal association cortices. Neural populations in the entorhinal cortex receive both unimodal and polymodal sensory information (Lopez De Silva et al., 1985; Vinogradova, 1975). Interestingly, although the degree of multimodal convergence is about 60%, different modalities and even stimuli within the same modality (e.g., tones of different frequencies) produce different activity patterns (Vinogradova, 1975).

Layer II in the lateral portions of the entorhinal cortex, which receive neocortical inputs, innervates the caudal dentate gyrus, and layer II in the medial portions of the entorhinal cortex, which receive limbic inputs, innervates rostral levels of the dentate gyrus (Ruth, Collier, & Routtemberg, 1982, 1988). According to Squire et al. (1989) and Amaral and Witter (1989) there is a considerable convergence of entorhinal cells on granule cells. The axons of the granule cells (the mossy fibers) connect to CA3 pyramidal cells. According to Squire et al. (1989) and Amaral and Witter (1989) the dentate gyrus–CA3 projection is the most lamellar of all intrahippocampal connections.

Pyramidal cells in CA3 originate an associational projection that connects all the rostrocaudal levels of the CA3 region. Schaffer collaterals originating in CA3 pyramidal cells also innervate CA1 pyramidal cells. The Schaffer collaterals arising from any particular level of CA3 terminate throughout much of the rostrocaudal levels of the CA1 region. Therefore, the CA3 field has associational connections that link all rostrocaudal levels of the hippocampus. These connections allow inputs at one rostrocaudal level to influence processing at all other levels of the hippocampus. Interestingly, different subsets of CA1 cells are activated by CA3 cells located in different transverse positions. In addition to its CA1 projections, CA3 cells project to the lateral septum through the fornix.

The CA1 field projects primarily to the subiculum, which in turn projects to the anterior thalamus, mammillary nucleus, and to layers II and III in the entorhinal cortex. Cells in the entorhinal cortex that do not project to the dentate gyrus project to the parahippocampal gyrus, the orbitofrontal cortex, and the insula.

In summary, Squire et al. (1989) and Amaral and Witter (1989) advocate the idea that the hippocampus is a three-dimensional region with important information processing taking place in both the lamellar and rostrocaudal axes.

Long-Term Potentiation and Afterhyperdepolarization Effects

The functional connectivity of the hippocampal circuitry can be modified either by changing the efficacy of several of its synapses (LTP) or by reducing the afterhyperdepolarization (AHP) of some its neurons. LTP has been found in different hippocampal synapses, including perforant path–dentate gyrus synapses, mossy fiber–CA3 synapses, Schaffer collateral–CA1 synapses, CA3–contralateral CA3 synapses, and perforant path–CA1 synapses (see Bliss & Lynch, 1988, for a review). Recently, Yeckel and Berger (1989) found LTP in perforant path–CA3 synapses. Decreased AHP has been reported in CA1 pyramidal cells (Disterhoft, Coulter, & Alkon, 1986, 1988).

Several approaches have been undertaken to study the relationships between plastic changes in the hippocampal circuit and classical conditioning. One approach is to determine functional changes in the hippocampus generated during classical conditioning. Weisz, Clark, and Thompson (1984) demonstrated that the efficacy of the perforant path–dentate gyrus granule cell synapse is increased during classical conditioning of the rabbit NM response. Also using the rabbit NM preparation, LoTurco, Coulter, and Alkon (1988) showed that classical conditioning enhances the subsequent synaptic potentials induced by high-frequency stimulation of the Shaffer–CA1 pyramidal cell synapse. This enhancement may be due to a decrease in the AHP of CA1 pyramidal cells (Disterhoft, et al., 1986; Disterhoft, Coulter, & Alkon, 1988; Disterhoft, Golden, Read, Coulter, & Alkon, 1988).

A second approach to the study the relationships between plastic changes in the hippocampal circuit and classical conditioning is to investigate the effect of LTP induction on different classical conditioning paradigms. Berger (1984) found that entorhinal cortex stimulation that produced LTP increased the rate of acquisition of a two-tone classical discrimination of the rabbit NM response. Recently, Robinson, Port, and Berger (1989) showed that kindling of the hippocampal perforant path–dentate gyrus projection (a procedure that, among other effects, induces LTP) facilitates discrimination acquisition but impairs discrimination reversal.

A third approach to the study of the correlation between hippocampal plastic changes and classical conditioning is to block endogenous LTP and to determine the effect on classical conditioning. Although the effect of LTP blockade has not yet been studied in classical conditioning, it has been examined in spatial learning. For instance, Morris, Anderson, Lynch, and Baudry (1986) showed that application of D-amino-phosphovalerate (APV), an antagonist of the *N*-methyl-D-aspartate (NMDA) class of glutamate receptor, impairs spatial learning in a water maze task but not a visual discrimination task. Similarly, application of protein kinase C inhibitors, which block LTP maintenance (Lovinger, Wong, Murakami, & Routtenberg, 1987), attenuates learning of a passive avoidance task (Ali, Bullock, & Rose, 1988).

Based on data from Levy and Steward (1979), Levy, Brassel, and Moore (1983) described an associative synaptic learning rule of the perforant path–dentate gyrus that describes how that pre- and postsynaptic activity regulate LTP. Levy et al. (1983) proposed that perforant path–dentate gyrus synapses change according to $m = y(hx - m)$, where m is the current value of the synaptic efficiency, x is the frequency of the presynaptic activity, y is the net amount of postsynaptic excitation, and h is a positive constant. According to Levy

et al. (1983), LTP increases when pre and postsynaptic neurons are active together ($y > 0$ and $x > 0$) and decreases when the postsynaptic neuron is active ($y > 0$) but the presynaptic neuron is inactive ($x = 0$). In agreement with Levy and Steward (1979), Kelso, Ganong, and Brown (1986) found, in accordance with Hebb's postulate for learning, that repetitive postsynaptic spiking enabled enhancement of CA3–CA1 synapses that showed concurrent presynaptic activity. However, in contrast with Levy and Steward (1979), Stanton and Sejnowski (1989) found that LTP in subiculum–CA1 synapses decreases when the potentiated input is active in the absence of activation of the postsynaptic neuron.

In summary, the connectivity of hippocampal neurons undergoes endogenous changes during classical conditioning, and when these changes are externally induced, classical conditioning is facilitated. The rules that govern changes in neural connectivity through LTP have been experimentally assessed.

Neuronal Activity

In the rabbit NM preparation, hippocampal activity during classical conditioning is positively correlated with the topography of the CR. During acquisition, increments in hippocampal unit activity precede the acquisition of the NM CR by over 100 trials (Berger, Alger, & Thompson, 1976). More specifically, Berger and Thompson (1978b) and Berger, Rinaldi, Weisz, and Thompson (1983) found that CA1 and CA3 pyramidal cells were characterized by an increase in frequency of firing over conditioning trials and by a within-trials pattern of discharge that models the NM response. Berger, Clark, and Thompson (1980) found that the activity correlated with the CR was present also in the entorhinal cortex but was amplified over trials in CA1 and CA3 hippocampal regions. Lesions of the dentate and interpositus cerebellar nuclei ipsilateral to the trained eye caused abolition of both the CR and the conditioned increases in hippocampal CA1 neural activity evoked by the CS (Clark et al., 1984). During extinction, Berger and Thompson (1982) found that pyramidal cells in the dorsal hippocampus decreased their frequency of firing correlated with behavioral extinction during the US period but in advance to behavioral extinction during the CS period. Hoehler and Thompson (1980) observed that when the ISI was changed, the peaks of both the hippocampal unit response and the behavioral topography shifted in the same direction. Solomon, Vander Schaaf, Thompson, and Weisz (1986) reported that during trace conditioning, there was a significant increase in hippocampal CA1 activity during the CS and trace period early in conditioning. Later in conditioning there was no neural activity during the CS period but only during the trace interval.

In addition to CR-related neural activity, other types of activity have been also recorded from hippocampal regions. For instance, Vinogradova (1975) found that neural activity in CA3 and CA1 pyramidal neurons, the dentate gyrus, and the entorhinal cortex of the rabbit was correlated with the presentation of sensory stimuli (tones and light). Activity in CA3 and CA1 showed habituation after repeated presentation of the stimuli. Berger et al. (1983) also reported that theta-cells respond during paired conditioning trials with a rhythmic 8-Hz bursting pattern. Weisz et al. (1984) found that granule cells in the dentate gyrus exhibited a CS-evoked theta firing when rabbits were trained with a CS followed by a US but not when they were trained with CS and US unpaired presentations.

In summary, in the rabbit NM preparation, neural activity in the hippocampus is correlated with the temporal topography of the NM response and the presentation of sensory stimuli.

Hippocampal–Cerebellar Regional Interactions in Classical Conditioning

As already mentioned, the hippocampus is not essential for the acquisition or maintenance of classical conditioning. Instead, experimental evidence from the NM response preparation suggests that the association of the CS representation and the US would be mediated by plastic changes at the interpositus nucleus of the cerebellum, at the Purkinje cells of the hemispheric portion of cerebellar lobule VI, or at both (see Thompson, 1986, for a review). Sensory representations of the CS reach the interpositus nucleus and the cerebellar cortex via mossy fibers from the pontine nuclei, and the US reaches the interpositus nucleus and the cerebellar cortex via climbing fibers from the inferior olive. CR representation activity originates in the cerebellar lobule VI, the interpositus nuclei, or both, is relayed to the contralateral red nucleus, and reaches the contralateral accessory abducens nuclei where the NM response is controlled.

As already mentioned, the activity of pyramidal cells in the dorsal hippocampus correlates with the topography of rabbit NM response. Clark et al. (1984) found that this hippocampal neuronal activity disappears after cerebellar ablation, supporting the idea that CS–US associations are stored in cerebellar areas and not in the hippocampus. Information about the behavioral response might be conveyed to the hippocampus through cerebellar–thalamic–cortical pathways (see Ito, 1984).

The hippocampus might modulate classical conditioning of the NM through several pathways. A hippocampal–retrosplenial cortex projection via the subiculum reaches the ventral pons (Berger, Bassett, & Weikart, 1985; Berger, Swanson, Milner, Lynch, & Thompson, 1980; Berger et al., 1986; Semple-Rowland, Bassett, & Berger, 1981). A cingulopontine projection has been described by Weisendanger and Weisendanger (1982) and confirmed by Wyss and Sripanidkulchai (1984). By modulating the pontine nucleus and thereby its mossy fiber projections to the cerebellar cortex and interpositus nucleus, hippocampal–cerebellar projections would modulate learning processes in the cerebellum (Berger et al., 1986; Steinmetz, Logan, & Thompson, 1988).

In summary, CS sensory representation–US associations seem to be stored in cerebellar regions, and information about these associations are relayed to the hippocampus, which in turn might modulate the activity of the sensory input to cerebellar areas.

The STM Regulation Hypothesis of Hippocampal Function

Grossberg's (1975) Attentional Network

Briefly, Grossberg's (1975) theory suggests that a CS activates neural populations whose activity constitutes a sensory representation, or short-term memory (STM), of the CS. A US activates neural populations of the drive representation of the US. Sensory representations compete among themselves for a limited-capacity STM activation that is reflected in a long-term memory (LTM) storage. The pairing of a CS with a US causes a long-term association of the sensory representation of the CS with the drive representation of the US (conditioned reinforcement learning). In addition, the pairing of the CS with the US causes a second long-term association of the drive representation of the US with the sensory representation of CS ("incentive motivation" learning). (Although incentive motivation has mainly an appetitive connotation, in the Grossberg model the term applies to both appetitive and aversive USs). Incentive motivation associations reflect the association of the US with a CS representation and mediate the enhancement of the sensory representation of the CS according to the strength of this association.

An attentional network based on Grossberg (1975) architecture is shown in Figure 1. A CS activates sensory-representation nodes (X_{i1}). According to Grossberg (1975) and in agreement with Hebb (1949), STM is sustained by a positive feedback loop. A US activates neural populations of the drive representation (Y). Simultaneous activation of the drive representation and CS sensory representations causes X_{i1} to become associated with the output of the drive representation. This LTM association is implemented by an increase in the synaptic weight (V_i). After X_{i1} becomes associated with the drive representation, Y, it becomes a secondary reinforcer for other CSs. In the original Grossberg model, simultaneous activation of the drive representation and a sensory representation causes the drive representation Y to become associated with X_{i1}. In the present rendering of the Grossberg network, simultaneous activation of the drive representation and a sensory representation causes X_{i1} to become associated with the drive representation Y. This LTM association is implemented by an increase in the synaptic weight (Z_i). Conditioning of the X_{i1}–X_{i2} pathway increases X_{i1} sensory representation by incentive motivation. A sensory cue with large V_i and Z_i can augment the STM activity of its sensory representation. Sensory representations compete among themselves for a limited STM capacity, which is implemented by letting STM activity X_{i1} be excited by CS_i and inhibited by the sum of all other STM activities, $\Sigma_{j \neq i} X_{j1}$. Through this competition, CSs with strong V_i and Z_i inhibit CSs with weak V_i and Z_i.

STM activity translates into permanent LTM traces. Stimuli with strong STM (strong sensory representations) change their V_i and Z_i faster than stimuli with weak STM. Therefore, stimuli with strong STM acquire stronger V_i associations than stimuli with weak STM, when presented with the US. The way STM activation is reflected in LTM storage in different

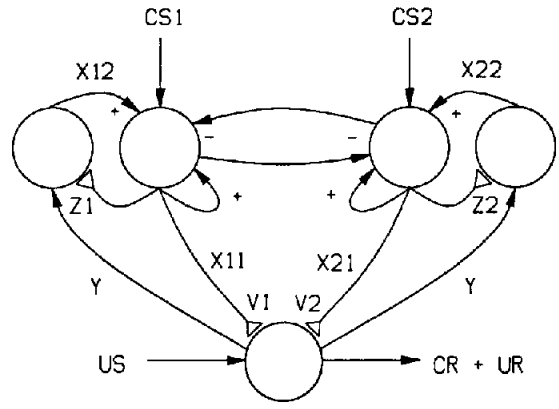

Figure 1. Diagram of Grossberg's (1975; Grossberg & Levine, 1987) attentional network for classical conditioning. (Conditioned stimuli, CS_1 and CS_2, activate sensory representations, X_{11} and X_{21}, which compete among themselves for a limited capacity short-term memory. Sensory representations, X_{11} and X_{21}, become associated with the unconditioned stimulus [US] by changing synaptic weights V_1 and V_2 [conditioned reinforcement learning]. X_{11} and X_{21} also become associated with output Y by changing synaptic weights Z_1 and Z_2 [incentive motivation learning]. Arrows represent fixed connections. Triangles represent modifiable connections.)

classical conditioning paradigms will be illustrated throughout the text. A formal description of the model is presented in Appendix A.

In summary, the Grossberg network comprises STM variables (sensory representations, X_{i1}, incentive motivation representations, X_{i2}, and drive representations, Y), that refer to the activity of neural populations and LTM variables (CS representation–US associations, V_i, and incentive motivation associations, Z_i) that refer to the connectivity between neural populations. STM is modulated by three circuits: (a) an incentive motivation loop ($X_{i1} - X_{i2} - X_{i1}$), (b) a competition loop ($\Sigma_{j \neq i} X_{j1}$), and (c) a self-excitation loop (X_{i1}). STM activity translates into permanent LTM traces.

A Neural Model of Hippocampal–Cerebellar Interactions

Because Grossberg's model is described as a neural architecture, the STM regulation hypothesis can be defined by specifying which nodes and connections in Grossberg's neural network are part of different brain circuits. Consequently, this section describes how nodes and connections might be mapped onto different brain regions under the constraints of the regional hippocampal–cerebellar circuits already described. This mapping refers mainly to the rabbit NM preparation.

In the Grossberg and Levine (1987) network, the level of processing assigned to CS_i (selective attention), is determined by the magnitude of the sensory representation (X_{i1}) stored in STM. In the network shown in Figure 1, STM is modulated by three circuits: (a) an incentive motivation loop ($X_{i1} - X_{i2} - X_{i1}$), (b) a competition loop ($\Sigma_{j \neq i} X_{j1}$), and (c) a self-excitation loop (X_{i1}). Because classical conditioning paradigms

involving selective attention are impaired by HL, Schmajuk and DiCarlo (1989) suggested that these circuits are part of the hippocampus. Because these circuits modulate STM, Schmajuk and DiCarlo referred to this hypothesis as the STM regulation hypothesis of hippocampal function.[1]

In view that (a) classical conditioning is still possible after hippocampal lesions, (b) classical conditioning is not possible after cerebellar lesions, and (c) induction of hippocampal LTP does not cause classical conditioning (but only facilitates discrimination acquisition), we propose that associations between sensory representations and the US, V_i, are stored in cerebellar areas, thereby controlling the generation of CRs. To the extent that (a) the activity of pyramidal cells in the hippocampus reflects the temporal topography of rabbit NM responses and (b) this neural activity depends on the integrity of cerebellar circuits, we assume that an output copy of the CR is relayed from cerebellar areas to the hippocampus.

Because endogenous hippocampal LTP is found during classical conditioning, we suggest that incentive motivation associations, Z_i, are stored in the hippocampus in the form of LTP. Importantly, rules describing changes in Z_i in the model (see Appendix A) are similar to those describing changes in hippocampal LTP (Kelso et al., 1986; Stanton & Sejnowski, 1989). Because hippocampal lesions seem to impair savings effects (see *Acquisition–Extinction Series: Savings Effects*), we assume that Z_i changes at a slower rate than V_i does. This rate difference implies that incentive motivation associations stored in the hippocampus are not lost even when X_{i1}–US cerebellar associations, V_i, have been extinguished (i.e., the hippocampus has a memory of past associations even when they have been extinguished in the cerebellum).

Finally, because the hippocampus projects to the sensory inputs to cerebellar areas in the pontine nuclei through retrosplenial and cingulate pathways, we suggest that hippocampal outputs controlling self-excitation (X_{i1}), incentive motivation (X_{i1}–Z_i), and competition ($\Sigma_{j\neq i}X_{j1}$) act on the pontine nuclei, modulating the magnitude of sensory representations that reach the cerebellum.

Figure 2 shows a schematic diagram of the hippocampal–cerebellar interconnections and the mapping of variables in the Grossberg (1975) model according to the STM regulation hypothesis. Sensory representations X_i at the pontine nuclei are modulated by inputs from the retrosplenial cortex before acting on cerebellar areas. In the cerebellum, these sensory representations are associated with US information arriving from the inferior olive. The cerebellar output (Y) reflects the magnitude of the X_i–US association, V_i, and generates a CR by acting on the red nucleus. An output copy of Y and sensory representation X_i are relayed from cerebellar areas to the thalamus and eventually to the entorhinal cortex and the hippocampus. Information about (a) incentive motivation (X_{i2}), (b) competition ($\Sigma_{j\neq i}X_{j1}$), and (c) self-excitation (X_{i1}) is computed in the hippocampus. Hippocampal outputs regulate sensory representations at the pontine nuclei through retrosplenial pathways, thereby controlling changes in cerebellar associations, V_i.

Lesions of the hippocampus produce important changes in STM. First, sensory representations are no longer enhanced (through incentive motivation associations) by their previous pairing with the US. Second, sensory representations no longer compete for a limited capacity STM. Third, sensory representations are shorter because they are no longer enhanced through self-excitation. Fourth, the remaining circuit cannot store incentive motivation values in LTM. Notwithstanding all these changes in STM, the system is still capable of storing V_i associations in cerebellar areas.

A Neural Model of the Hippocampus

The previous section defined the STM regulation hypothesis by proposing how nodes and connections regulating attention in Grossberg's (1975) neural network are mapped onto hippocampal–cerebellar regional circuits. This section attempts to map the network onto the intrinsic circuitry of the hippocampus. The result is entirely compatible with the STM regulation hypothesis; that is, nodes and connections assumed to be part of the hippocampus are now mapped onto a three-dimensional intrinsic hippocampal circuit. Whereas the regional hippocampal-cerebellar mapping contemplates the problem of hippocampal function, the intrinsic mapping concerns the problem of the function of the different hippocampal fields.

The mapping of the Grossberg network onto the intrinsic circuit of the hippocampus is constrained by the three-dimensional organization of the hippocampus, the firing characteristics of hippocampal neurons, and the hippocampal distribution of potentiable synapses, cited previously (see Neurological Constraints). Figure 3 shows a schematic diagram of some of the major intrinsic connections of the hippocampal circuitry, based on Shepherd (1979) and Squire et al.'s (1988) descriptions. Variables in the Grossberg model have been mapped onto this diagram under the considerations presented next.

As mentioned before, Berger et al. (1976; 1983) and Berger and Thompson (1978a) found that neurons in entorhinal cortex and CA1 and CA3 pyramidal cells modeled the behavioral response. In consequence, the neural network shown in Figure 3 shows a copy of the behavioral response, Y, present in entorhinal cortex and relayed to CA3 and CA1 regions.

Vinogradova's (1975) data show that neural activity in CA3 and CA1 pyramidal neurons, the dentate gyrus, and the entorhinal cortex is correlated with the presentation of sensory stimulus. Therefore, Figure 3 shows sensory representations X_{i1} in these regions. In agreement with Vinogradova's (1975) data, the activity of these neurons extends well beyond the duration of the physical stimulation, in a way that resembles the sensory representations X_{i1} described in the pres-

[1] The Schmajuk and DiCarlo (1989) approach differs from Grossberg's (1975) suggestion that sensory representations X_{i1}, the self-excitation loop, and incentive motivation associations Z_i were located in the neocortex and that self-excitation and competition among drive representations and V_i associations were located in the hippocampus.

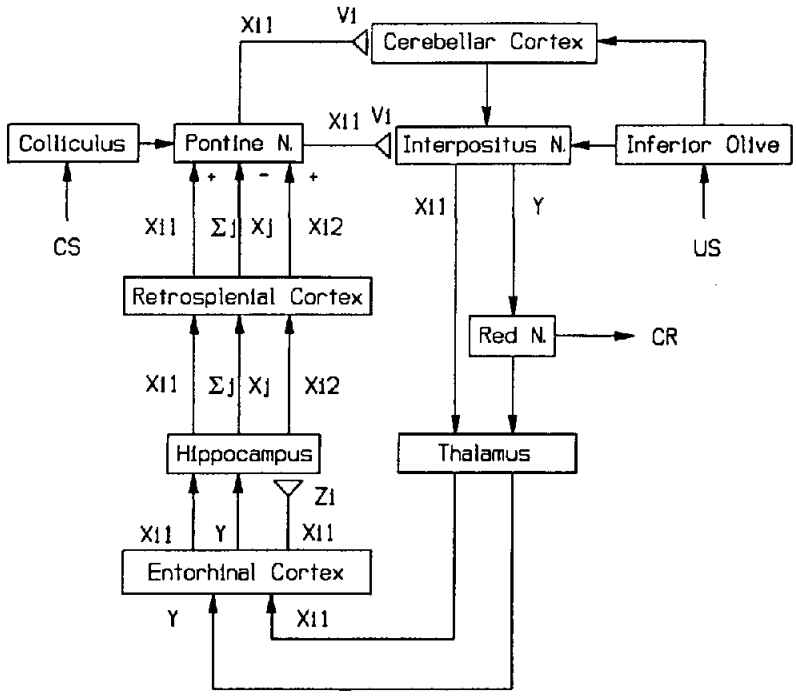

Figure 2. The short-term memory regulation hypothesis: Mapping of Grossberg's (1975) network onto a schematic diagram of hippocampal–cerebellar interconnections. (A conditioned stimulus, CS, activates a sensory representation, X_{i1}, in the colliculus and is relayed to the pontine nuclei. Sensory representation X_{i1} becomes associated with the unconditioned stimulus [US] by changing synaptic weights V_i, possibly either in the interpositus nucleus or cerebellar cortex. X_{i1} becomes associated with output Y by changing synaptic weights Z_i, in the form of hippocampal long-term potentiation. Sensory representations compete among themselves for a limited capacity short-term memory [STM]. Sensory representations also sustain a self-excitatory feedback loop. Hippocampal lesions preserve CS–US connections but eliminate hippocampal modulation of STM of sensory representations at the pontine nuclei. Arrows represent fixed connections. Triangles represent modifiable connections.)

ent article (see *Acquisition of Delay and Trace Conditioning*). Figure 3 shows pyramidal cells labeled X_{11} and X_{21} that receive sensory representations X_{11} or X_{21} from the entorhinal cortex. These populations are assumed to be part of the positive feedback loop in the Grossberg model.

The mapping of synapses storing incentive motivation associations Z_i (i.e., the association between sensory representations X_i with CR-related activity Y) is successively constrained by different pieces of experimental data. First, Z_i can be mapped only onto hippocampal synapses that show LTP (perforant path–CA3, perforant path–CA1, Schaffer collateral–CA1, CA3–contralateral CA3, perforant path–dentate gyrus, mossy fiber–CA3 synapses). Second, Z_i represents the connection strength between a neuron coding sensory representation X_i with a neuron that receives CR-related information Y (perforant path–CA3, perforant path–CA1, Schaffer collateral–CA1, mossy fiber–CA3 synapses). Third, data showing that neural activity in entorhinal cortex might be amplified (Berger et al., 1980) or attenuated (Vinogradova, 1975) in region CA3 suggest that Z_i represents the variable connection strength of a synapse between the entorhinal cortex and CA3 (a perforant path–CA3 NMDA synapse or a mossy fiber–CA3 non-NMDA synapse). Fourth, in view that the rules describing changes in Z_i in the model (see Appendix A) are similar to those describing changes in LTP at NMDA synapses (Kelso et al., 1986; Stanton & Sejnowski, 1989), we assume that Z_i represents the plastic connectivity of the perforant path–CA3 NMDA synapse. Figure 3 shows CA3 pyramidal cells labeled X_{12} and X_{22} that receive a strong CR-related input Y and a weak sensory input X_{11} or X_{21} from the entorhinal cortex. The output of these neurons, proportional to the weak input X_{i1} multiplied by the weight of the modifiable synapse Z_i, is conveyed to the CA1 regions. These pyramidal populations are assumed to be part of the incentive motivation loop in the Grossberg model.

Amaral and Witter's (1989) data show that the hippocampus is a three-dimensional region and that information processing takes place both in the lamellar axes and the rostrolcaudal axis. Therefore, Figure 3 shows that pyramidal cells labeled X_{11} and X_{21} in the CA1 region receive sensory representations from a different lamella. To compute $\Sigma_{j \neq i} X_{j1}$, these populations should receive inputs from many rostrocaudal levels of the hippocampus. These populations are assumed to be part of the competition loop in the Grossberg model.

Finally, the outputs of CA1 integrating positive feedback,

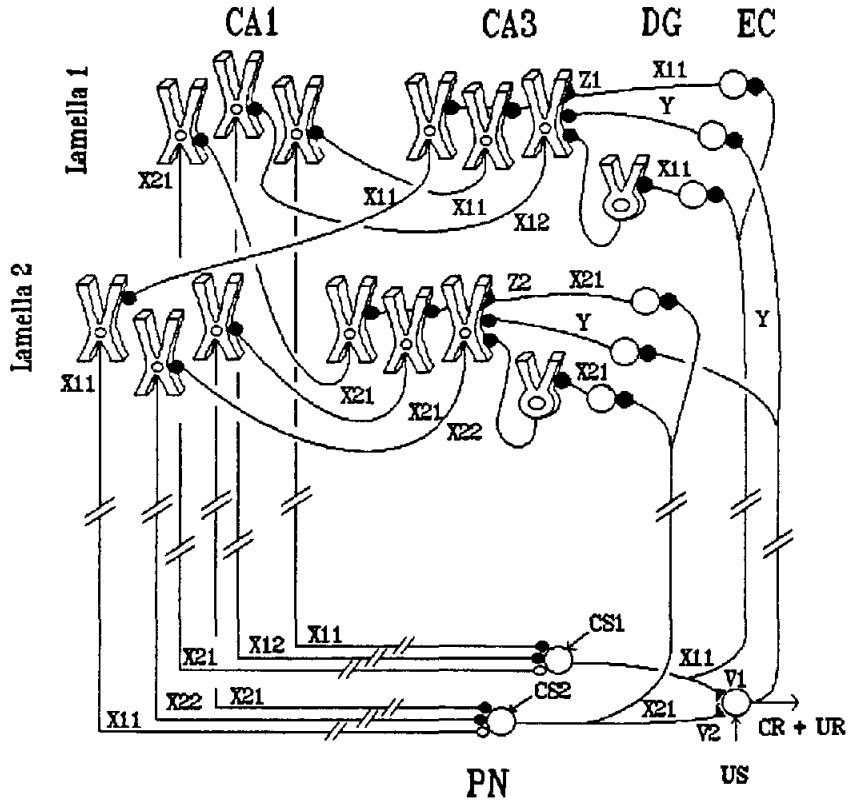

Figure 3. The short-term memory regulation hypothesis: Mapping of Grossberg's (1975) network onto a three-dimensional schematic diagram of the hippocampal circuit. (The basic circuit diagram of the hippocampus includes two hippocampal lamellas, each one drawn after Shepherd [1979]. CA1 = region superior; CA3 = regio inferior; DG = dentate gyrus; EC = entorhinal cortex; PN = pontine nuclei. Circuits regulating short-term memory by storing incentive motivation values [Z_1 and Z_2], mediating self-excitation, and mediating competition among sensory representations are assumed to be part of the hippocampal circuit. Circuits storing conditioned stimulus–unconditioned stimulus [CS–US] associations [V_1 and V_2] are assumed to be in cerebellar areas of the brain. Solid circles represent fixed excitatory connections, open circles represent fixed inhibitory connections, and triangles represent modifiable excitatory connections.)

incentive motivations, and competition loops regulate, through inhibitory and excitatory pathways, sensory representation activities (X_{11} and X_{21}) in cerebellar areas where the LTM of X_i–US associations is stored.

Computer Simulations

Within the framework of the circuit presented in Figure 2, the effect of hippocampal manipulations are easily described: Hippocampal lesions eliminate incentive motivation, competition, and self-excitation among sensory representations; induction of hippocampal LTP increases the stored values of incentive motivation of all stimuli; and LTP blockade maintains constant values of incentive motivation of all stimuli. A formal description of these manipulations is presented in Appendix B.

The following sections contrast experimental results regarding hippocampal manipulations in classical conditioning with computer simulations using the neural model presented in Figure 2. Parameters used in the simulations are shown in Appendix C. Simulated hippocampal manipulations include HL, induction of hippocampal LTP, hippocampal kindling, and blockade of hippocampal LTP in the following paradigms: (a) acquisition of delay and trace conditioning, (b) extinction of delay and trace conditioning, (c) acquisition–extinction series of delay conditioning, (d) latent inhibition, (e) blocking, (f) overshadowing, (g) discrimination acquisition, (h) discrimination reversal, and (i) secondary reinforcement.

Acquisition of Delay and Trace Conditioning

Experimental data. The effects of HL on acquisition of classical conditioning have been studied under a wide variety of experimental parameters, including different combinations of CS and US durations, ISIs, and types of US.

Acquisition of delay conditioning has been reported to be unaffected or facilitated by HL. Schmaltz and Theios (1972) found that HL animals showed faster acquisition using a 250-

Table 1
Experimental Results of the Acquisition and Extinction of Classical Conditioning After Lesions of the Hippocampal System

Reference	CS	US	ISI	Results
Berger and Orr (1983)	850 ms 1000 Hz 85 dB	100 ms airpuff 210 g/cm	750 ms	normal acquisition normal extinction
James, Hardiman, and Yeo (1987)	250 ms white noise 90 dB	50 ms shock 2.5 mA	750 ms	shorter onset latency normal acquisition
Moyer, Deyo, and Disterhoft (1990)	100 ms 6000 Hz 90 dB	150 ms airpuff 2.5 psi	300 ms	normal CR onset latency normal acquisition deficit in extinction
		150 ms airpuff 2.5 psi	500 ms	shorter CR onset latency deficit in acquisition
Port, Mikhail, and Patterson (1985)	800 ms tone 90 dB	50 ms shock 2.5 mA	150 ms	shorter CR onset latency faster acquisition
			300 ms	normal CR onset latency normal acquisition
			600 ms	normal CR onset latency normal acquisition
Port and Patterson (1984)	500 ms tone 90 dB	50 ms shock 2.5 mA	450 ms	shorter CR onset latency normal acquisition
Port, Romano, Steinmetz, Mikhail, and Patterson (1986)	250 ms tone 92 dB	50 ms shock 2.5 mA	750 ms	longer CR onset latency normal acquisition
	250 ms tone 90 dB	100 ms airpuff 210 g/cm	750 ms	shorter CR onset latency normal acquisition
Schmaltz and Theios (1972)	250 ms 2000 Hz 92 dB	50 ms shock	250 ms	faster acquisition normal extinction
Solomon and Moore (1975)	450 ms 1200 Hz 76 dB	50 ms shock 2 mA	450 ms	normal acquisition
Solomon, Vander Schaaf, Thompson, and Weisz (1986)	250 ms white noise 85 dB	100 ms airpuff 3 psi	750 ms	shorter CR onset latencies slower acquisition

Note. CS = conditioned stimulus; US = unconditioned stimulus; ISI = interstimulus interval; CR = conditioned response.

ms CS, a 50-ms shock US, and a 250-ms ISI. Solomon and Moore (1975) found that HL animals displayed normal acquisition using a 450-ms CS, a 50-ms shock US, and a 450-ms ISI. Berger and Orr (1983) found normal acquisition, using a 850-ms CS, a 100-ms airpuff US, and a 750-ms ISI. Port and Patterson (1984) found that HL animals showed shorter CR onset latency and normal acquisition rate using a 500-ms CS, a 50-ms shock US, and a 450-ms ISI. Port, Mikhail, and Patterson (1985) found shorter CR onset latency and faster acquisition, using a 800-ms CS, a 50-ms shock US, and 150-ms ISI. When the ISI was extended to 300 ms, they found that HL animals showed normal CR onset latency, and normal acquisition. Finally, with a 600-ms ISI, they found that HL animals showed normal CR onset latency and acquisition.

Acquisition of trace conditioning has been reported to be impaired or unaffected by HL. Port, Romano, Steinmetz, Mikhail, and Patterson (1986) reported that HL rabbits showed longer CR onset latency and normal acquisition, using a 250-ms CS, a 50-ms shock US, and a 750-ms ISI. When the shock US was replaced by a 100-ms airpuff US, they found that HL animal showed shorter CR onset latency and normal acquisition. Solomon et al. (1986) reported shorter CS onset latencies and slower acquisition in HL rabbits using a 250-ms CS, a 100-ms airpuff US, and a 500-ms ISI. James, Hardiman, and Yeo (1987), reported normal acquisition and shorter onset latency, using a 250-ms CS, a 50-ms shock US, and a 750-ms ISI. Recently, Moyer, Deyo, and Disterhoft (1990) found normal CR onset latency, normal acquisition, using a 100-ms CS, a 150-ms airpuff US, and a 300-ms ISI. However, they found shorter CR onset latency and deficit in acquisition, when the ISI was 500 ms.

Table 1 shows a summary of the different results obtained with different CS and US durations, ISIs, and US types, during acquisition and extinction of conditioning. At a first sight, it seems difficult to find principles to decide whether or not a given experiment will be affected by hippocampal lesions. As we show later, it is the combination of variables used in the experimental design (e.g., the combination of CS duration and ISI) rather than the type of paradigm (e.g., delay

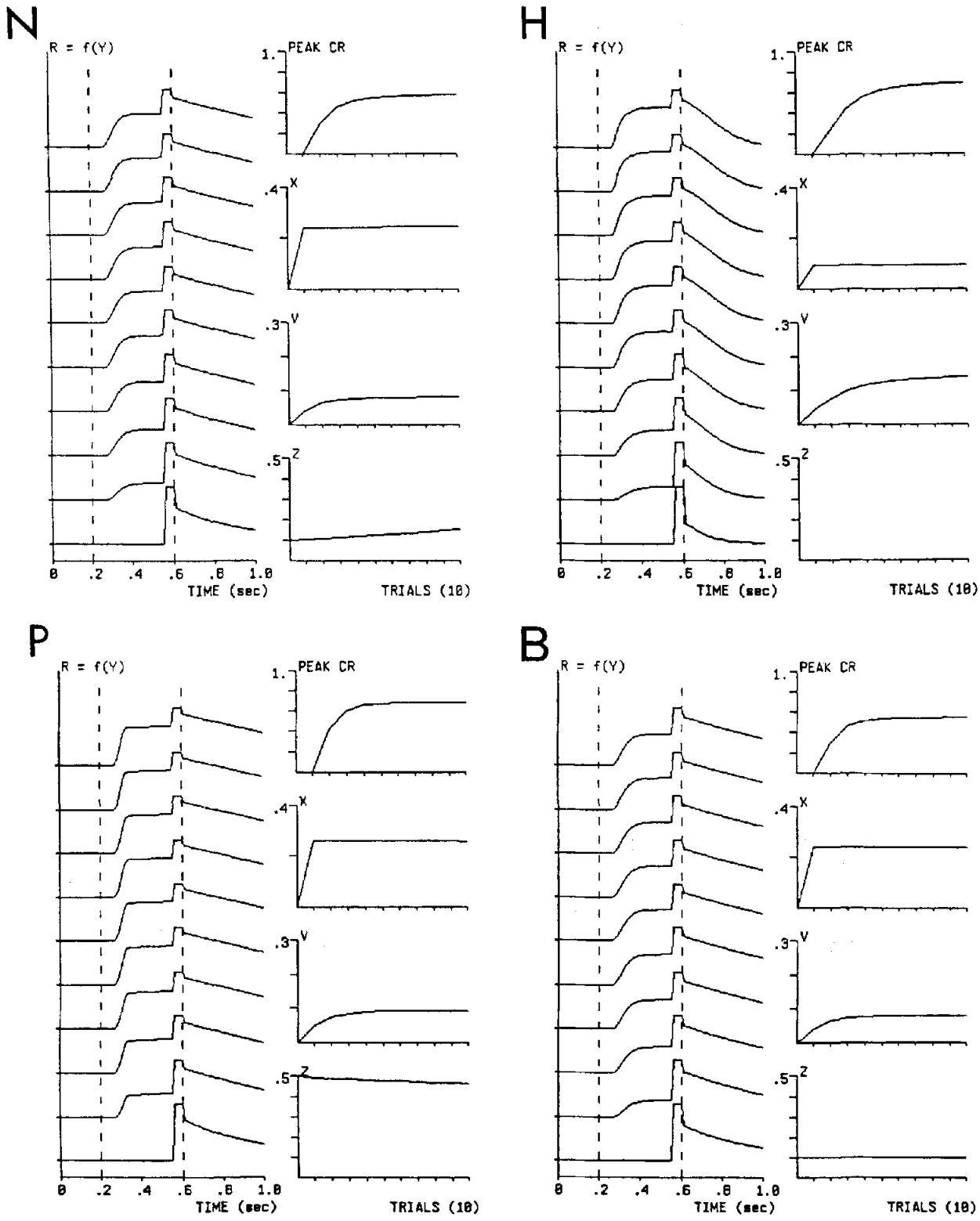

Figure 4. Effect of different hippocampal manipulations on acquisition of classical conditioning. (N = normal case; H = hippocampal lesion case; P = long-term potentiation [LTP] case; B = LTP blockade case. Left panels: Real-time simulated conditioned and unconditioned response in 10 reinforced trials. First trial is represented at the bottom of the panel. Right panels: Peak conditioned response [CR] = peak CR as a function of trials; X = average X_{11} as a function of trials; V = V_1 as a function of trials; Z = Z_1 as a function of trials.)

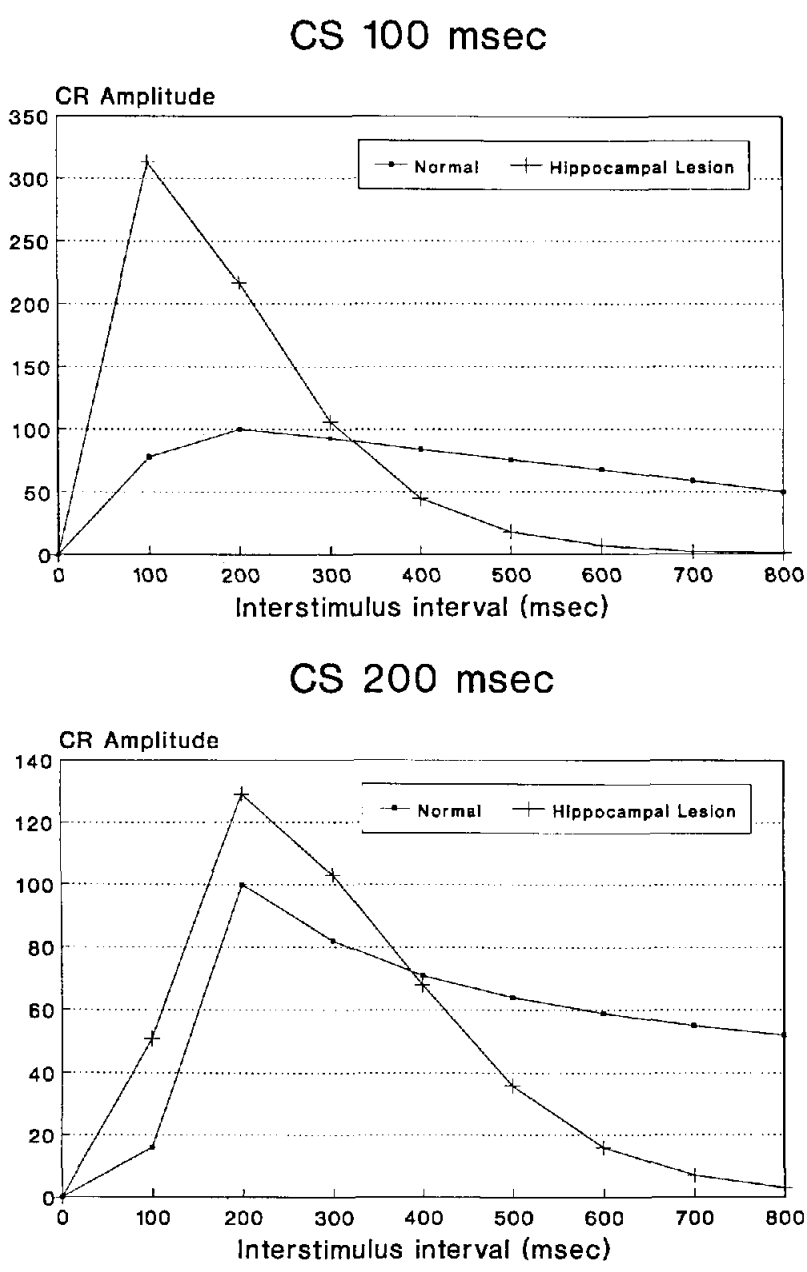

Figure 5. Effect of hippocampal lesions on interstimulus interval (ISI) curves. (Peak conditioned response [CR] amplitude for normal and hippocampal lesion cases after 20 reinforced trials for different ISIs and different conditioned stimulus durations [100 and 200 ms]. Peak CR amplitude is expressed as a percentage of the maximum peak CR of normal animals over all ISIs.)

vs. trace conditioning) that serves as a predictor for many experimental outcomes.

No data is available on the effect of LTP induction or LTP blockade on delay and trace conditioning.

Computer simulations. Figure 4 shows real-time simulations of 10 trials in a delay conditioning paradigm with a 400-ms CS, 50-ms US, and 350-ms ISI, for normal, HL, LTP induction, and LTP blockade cases. In the normal case, CR amplitude, X_1, V_1, and Z_1 increase over trials. In the HL case, CR amplitude and V_1 increase at the same rate as the normal case but both achieve a higher asymptotic value. Because Z_1 is always zero in the HL case, X_1 remains small and constant over trials. In the LTP case, because Z_1 and therefore X_1 are large, CR amplitude and V_1 increase over trials at a faster rate than in the normal case. Z_1 gradually decreases from its induced value to the value sustained by the network. Finally, in the LTP blockade case CR amplitude and V_1 increase over trials and achieve a slightly lower value than in the normal case. Because Z_1 is constant in the LTP blockade case, X_1 remains constant over trials.

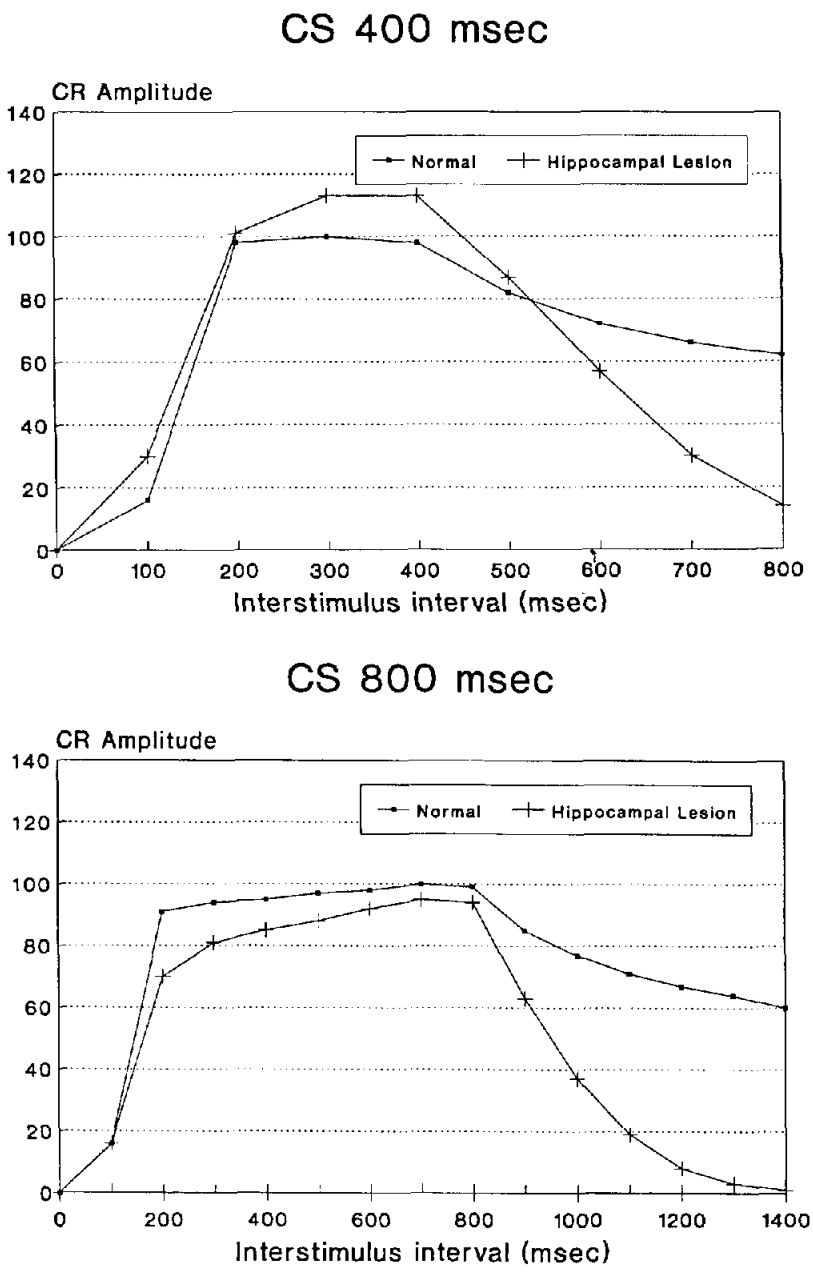

Figure 6. Effect of hippocampal lesions on interstimulus interval (ISI) curves. (Peak conditioned response [CR] amplitude for normal and hippocampal lesion cases after 20 reinforced trials for different ISIs and different conditioned stimulus durations [400 and 800 ms]. Peak CR amplitude is expressed as a percentage of the maximum peak CR of normal animals over all ISIs.)

Figures 5 and 6 show peak CR amplitude over 20 acquisition trials with 100-, 200-, 400-, and 800-ms CSs; 0-, 100-, 300-, 400-, 500-, 600-, 700-, and 800-ms ISIs (up to 1,400-ms ISIs for 800-ms CSs); and a 50-ms US, for normal and HL cases. Under delay conditioning with both 100-ms and 200-ms CSs, simulations for the HL case show stronger conditioning than the normal case (Figure 5). This result is in agreement with the Schmaltz and Theios (1972) finding that acquisition of delay conditioning was facilitated in HL rabbits with a 250-ms CS and a 250-ms ISI. Under trace conditioning with a 100-ms CSs, simulations show that trace conditioning is increasingly impaired with increasing ISIs in the HL case. In agreement with these results, Moyer, Deyo, and Disterhoft (1988, 1990) found that HL animals were impaired with a 500-ms ISI but not with a 300-ms ISI when a 100-ms CS was used.

Simulations show that trace conditioning is totally impaired in HL animals with a 500-ms ISI and a 100-ms CS but not with a 500-ms ISI and a 200-ms CS. These results are partly supported by experimental data. For example, when

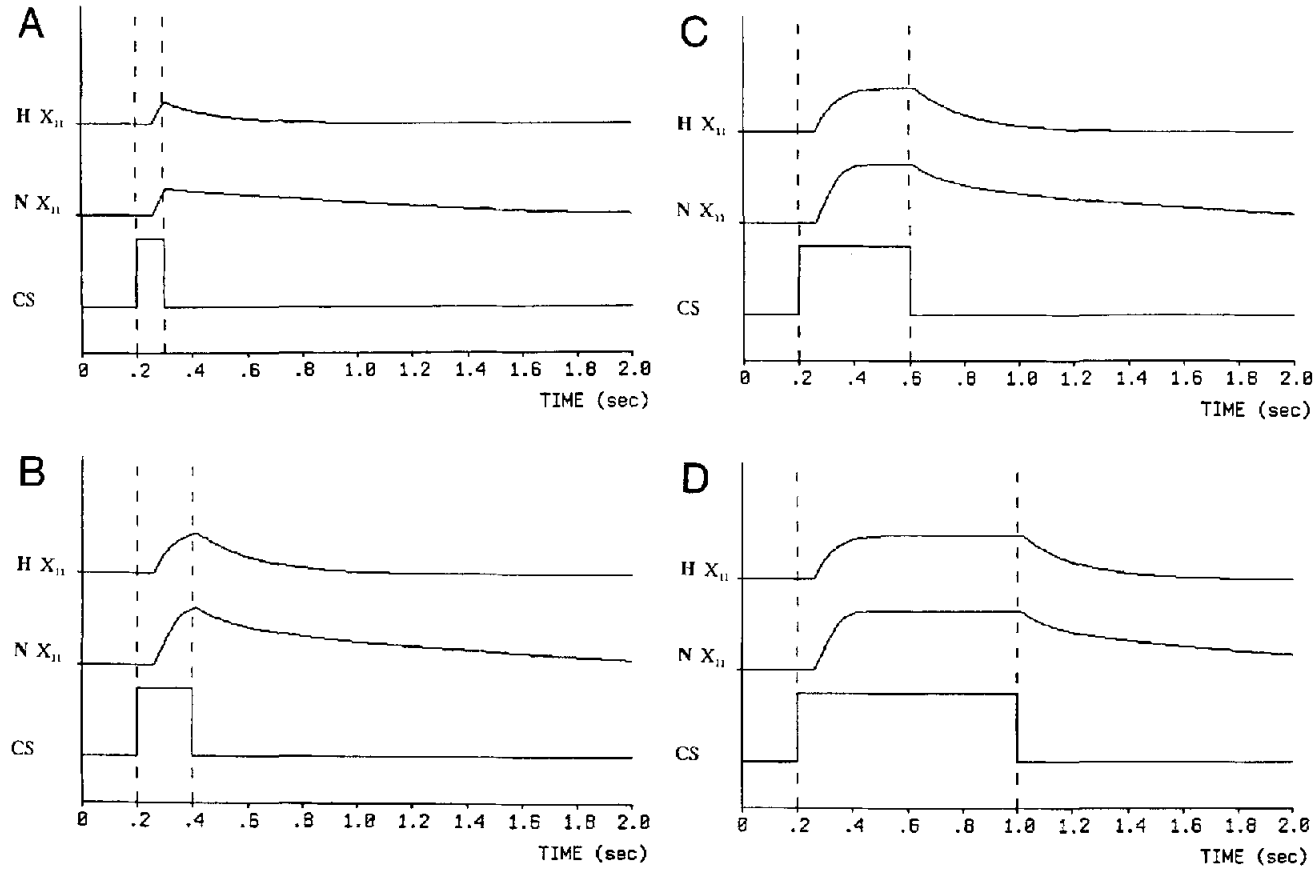

Figure 7. Effect of hippocampal lesions on sensory representations of a conditioned stimulus (CS) presented in isolation. (Sensory representations X_{i1} of normal [N] and hippocampal-lesioned [H] animals generated by [A] 100-ms CS, [B] 200-ms CS, [C] 400-ms CS, and [D] 800-ms CS.)

a 250-ms CS was used with a 750-ms ISI, HL rabbits showed partial or no impairment (James et al., 1987; Port, Romano, Steinmetz, Mikhail, & Patterson, 1986; Solomon et al., 1986). Simulations show that when a 400-ms CS is used, normal and HL animals behave in similar ways (Figure 6). This result is supported by Solomon and Moore's (1975) finding that HL animals displayed normal acquisition using a 450-ms CS and a 400-ms ISI. Finally, simulations with a 800-ms CS show that normal and HL animal have similar levels of acquisition for most ISI values (Figure 6).

In summary, according to Figures 5 and 6, the difference between normal and HL groups decreases as CS duration increases. When trained with short-duration CSs and short ISIs, HL animals show stronger conditioning than normals. When trained with short-duration CSs and long ISIs, HL animals show similar or worse conditioning than normals.

The results presented in Figures 5 and 6 can be explained in terms of the temporal attributes of the sensory representations of the CS. Figure 7 shows the sensory representations X_i for normal and HL cases with 100-, 200-, 400-, and 800-ms CSs. Sensory representations are increasingly longer with longer CSs. Notice that, because of the lack of self-excitation, sensory representations for the HL case are shorter than those for the normal case. Differences in the sensory representations of normal and HL animals do not imply the absence of conditioning and might result even in faster and stronger conditioning in the HL case. These changes in the topography of the sensory representation of a single CS explain the wide variety of results obtained in delay and trace conditioning after HL.

The association between sensory representations X_{i1} and the US, V_i, increases during the time when X_{i1} and the US overlap and decreases during the time when X_{i1} is presented alone (see Equation A8 in Appendix A). Therefore, the acquisition during a given trial is proportional to the difference between the area under the sensory representation X_{i1} curve during the time when the US is presented and the area under the sensory representation X_{i1} curve during the rest of the time. As the CS duration increases, the areas under the sensory representation curves of normal and HL animals become more similar (see Figure 7), and the difference between acquisition rates decreases. This attribute of the sensory representations explains why Schmaltz and Theios (1972) found that HL animals showed faster acquisition using a 250-ms CS but Solomon and Moore (1975) found that HL animals displayed normal acquisition using a 450-ms CS.

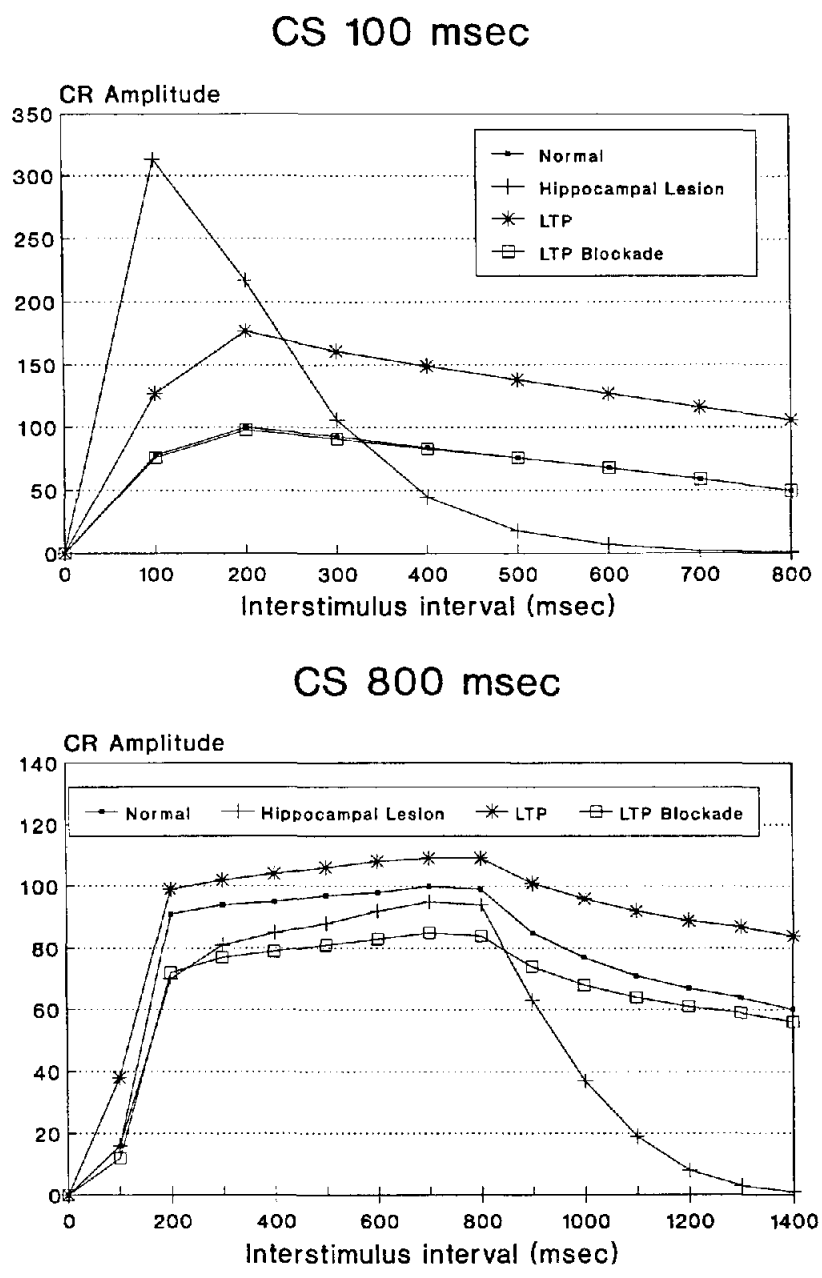

Figure 8. Effect of different hippocampal manipulations on interstimulus interval (ISI) curves. (Peak conditioned response [CR] amplitude for normal, hippocampal lesion, long-term potentiation [LTP], and LTP blockade cases after 20 reinforced trials for different ISIs and different conditioned stimulus durations [200 and 800 ms]. Peak CR amplitude is expressed as a percentage of the maximum peak CR of normal animals over all ISIs.)

Figure 7 also showed that for short CSs sensory representations in the normal case are active for a longer time than sensory representations in the HL case. Therefore, normal animals can accrue conditioning with ISIs at which HL animals cannot because their sensory representations are already inactive. This difference in the duration of sensory representations of normal and HL cases explains why Moyer et al. (1988) found that with a short (100-ms) CS, a 300-ms ISI produced no impairment in HL animals, but HL animals were impaired with a 500-ms ISI.

Figure 8 shows that LTP induction facilitates learning with both short and long CSs. Compared with the normal case, LTP blockade impairs acquisition of classical conditioning with long CSs but not with short CSs. This result is explained by the fact that long CSs accrue larger incentive motivation than short CSs in normal animals. Therefore, by comparison

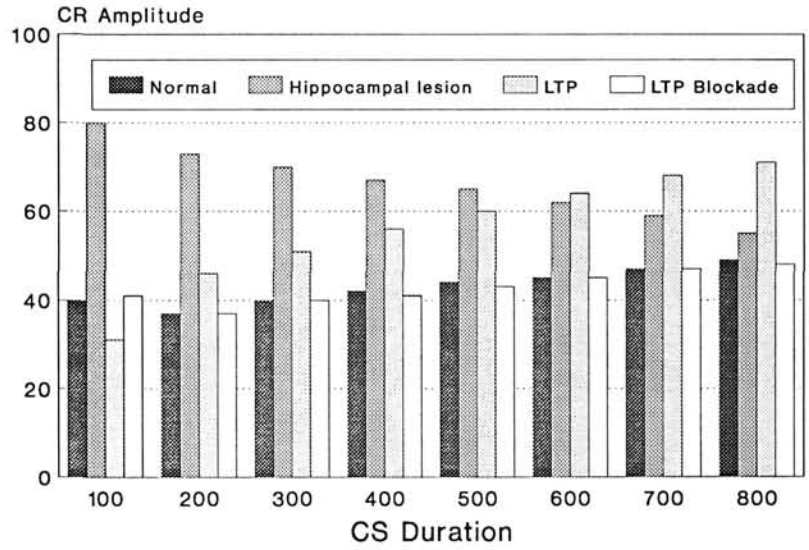

Figure 9. Effect of different hippocampal manipulations on extinction. (Percentage of peak conditioned response [CR] amplitude on the first nonreinforced trial after training to criterion [peak CR amplitude = 0.1] for different conditioned stimulus [CS] durations [100–800 ms] for normal, hippocampal lesion, long-term potentiation [LTP], and LTP blockade cases.)

the effect of LTP blockade becomes more apparent in the case of long CSs.

Extinction

Experimental data. Three studies describe the effect of HL on extinction. Berger and Orr (1983) found normal extinction, using a 850-ms CS, a 100-ms airpuff US, and a 750-ms ISI. Moyer et al. (1990) found impaired extinction using a 100-ms CS, a 150-ms airpuff US, and a 300-ms ISI. In an acquisition–extinction series of the NM response in rabbits, Schmaltz and Theios (1972) found that the first extinction appeared to be unaffected by HL. However, after alternating the acquisition–reacquisition series, normal rabbits decreased the number of trials to reach extinction criterion, whereas HL rabbits increased the number of trials to criterion, showing impairment in extinction.

No data is available on the effect of LTP induction or LTP blockade on extinction.

Computer simulations. Figure 9 shows simulated peak CR amplitude on the first extinction trial as a percentage of the peak CR amplitude on the last acquisition trial for different CS durations. All groups were trained to same criterion (peak CR amplitude = 0.1) with the ISI equal to the CS duration. According to Figure 9, HL impairs extinction only when short CSs are used but not with long CSs. These results are in agreement with experimental data. Moyer et al. (1990) found impairment in extinction with a 300-ms CS, whereas Berger and Orr (1983) reported normal extinction with an 800-ms CS. Simulations showing extinction impairment with a 200-ms CS are in disagreement with the first but in agreement with the second, third, and fourth extinction cycles in Schmaltz and Theios's (1972) acquisition–extinction series.

The results presented in Figure 9 can be also explained in terms of the sensory representations shown in Figure 7. As mentioned before, the association between sensory representations X_{i1} and the US, V_i, decreases during the time when X_{i1} is presented alone (Equation A8 in Appendix A). Therefore, extinction during a given trial is proportional to the area under the sensory representation X_{i1} curve. In consequence, because the normal case has longer sensory representations for short CSs than the HL case, the model predicts that normal animals show faster extinction than HL animals. As the CS duration increases, the difference in duration between the normal and HL sensory representations become smaller (see Figure 7) and therefore extinction rates also become more similar.

The model also predicts that LTP blockade does not change extinction substantially. Because increased incentive motivation translates into a larger X_{i1} thereby increasing the association of X_{i1} with the drive representation, and this association increases with increasing CS durations, the model predicts that LTP induction increasingly impairs extinction with increasing CS durations.

Acquisition–Extinction Series: Savings Effects

Experimental data. When acquisition is followed by extinction in a classical conditioning paradigm, normal animals show faster reacquisition (i.e., savings effects; Scavio, Ross, & McLeod, 1983). Schmaltz and Theios (1972) studied the effect of exposing rabbits to a successive acquisition and extinction series using a 250-ms CS, a 50-ms shock US, and a 250-ms ISI. Schmaltz and Theios (1972) found that HL animals show faster acquisition than normals in the first acquisition series but that they did not differ from normals in the first extinction series. In the following extinction series,

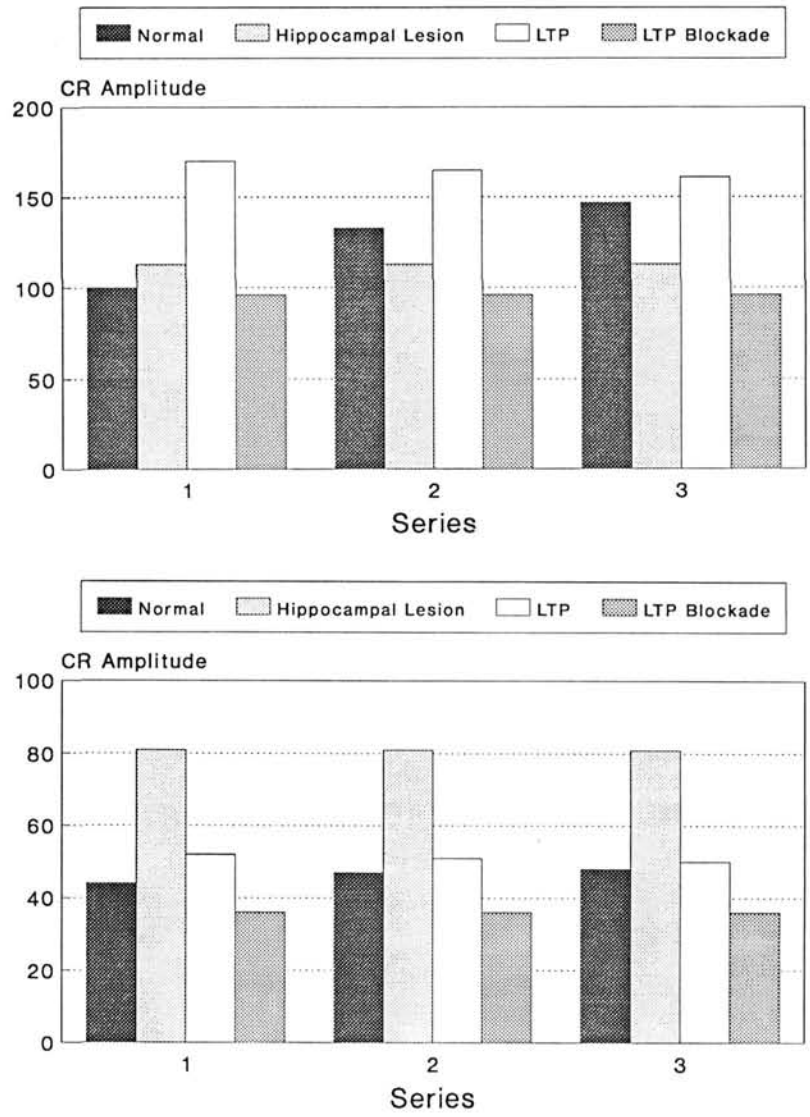

Figure 10. Effect of different hippocampal manipulations on the acquisition–extinction series. (Top panel: Acquisition. Peak conditioned response [CR] amplitude for normal, hippocampal lesion, long-term potentiation [LTP], and LTP blockade cases on three series of acquisition trials. Peak CR amplitude is expressed as a percentage of the peak CR of normal animals on the fourth acquisition trial of the first series. Bottom panel: Extinction. Percentage of peak CR amplitude on the first nonreinforced trial after 50 acquisition trials for normal, hippocampal lesion, LTP, and LTP blockade cases. Percentage is computed with respect to the peak CR at the end of each acquisition series.)

normal animals decreased the number of trials to reach criterion (show savings), whereas HL rabbits increased the number of trials to extinction criterion.

Computer simulations. Figure 10 (top panel) shows simulations of peak CR amplitude after three alternating acquisition–extinction series, each one with 50 acquisition and 10 extinction trials. Consistent with Schmaltz and Theios (1972), Figure 10 (top panel) shows that HL animals display faster acquisition than normals in the first acquisition series. In the normal case, X_{11} receives an increasing amount of incentive motivation over trials. As a result, after the first session acquisition proceeds faster in the normal (savings effect) but not in the HL case. Induction of LTP accelerates acquisition over all series. Consistently, LTP blockade prevents improvements in acquisition over all series.

Figure 10 (bottom panel) shows peak CR amplitude after 1 extinction trial expressed as the percentage of the peak CR amplitude on the last of 50 acquisition trials. In the normal case, the model predicts no improvement in extinction over series. These results are in disagreement with the acquisition–extinction series of the Schmaltz and Theios (1972) study showing that normal animals decreased the number of trials to extinction criterion. Also in conflict with Schmaltz and Theios' results, simulations do not show an increasing im-

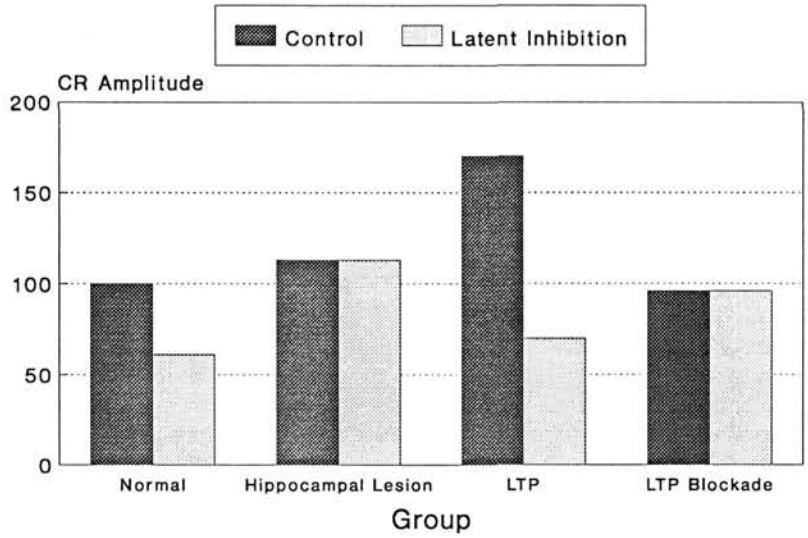

Figure 11. Effect of different hippocampal manipulations on latent inhibition. (Peak conditioned response [CR] amplitude for normal, hippocampal lesion, long-term potention [LTP], and LTP blockade cases after four acquisition trials and after 200 conditioned stimulus preexposure trials or 200 control trials. Peak CR amplitude is expressed as a percentage of the peak CR of normal control animals.)

pairment in extinction in HL animals but a deficit throughout all extinction series. Because increased incentive motivation translate into a larger X_{i1} thereby increasing the CR amplitude, the model predicts that LTP induction slightly impairs extinction over all series. Because LTP blockade impedes increases in incentive motivation that translates into a larger X_{i1} thereby increasing the CR amplitude, the model predicts that LTP blockade facilitates extinction over all series.

Latent Inhibition

Experimental data. In latent inhibition, animals are first preexposed to presentations of the CS alone followed by CS–US presentations. Preexposure usually produces retardation of the acquisition of CS–US associations. Solomon and Moore (1975) reported that animals with HL showed impaired latent inhibition after preexposure to a tone CS. Consistent with Solomon and Moore's result, MacFarland, Kostas, and Drew (1978) and Kaye and Pearce (1987a, 1987b) reported that HL attenuates latent inhibition.

No data is available on the effect of LTP induction or LTP blockade on latent inhibition.

Computer simulations. Figure 11 shows peak CR amplitude after 4 acquisition trials following 200 CS preexposure trials for normal, HL, LTP, and LTP blockade groups. In the present article, we assume that normal animals have an initial value of incentive motivation stored in the hippocampus. Because the initial value of incentive motivation decreases during CS preexposure in the normal case, the latent inhibition group shows slower acquisition than the control. Because the HL group does not store incentive motivation information (Z_i), the rate of acquisition is not modified by CS preexposure.

When latent inhibition is attempted after LTP induction, the LTP control group shows faster acquisition rates than normal controls, and the latent inhibition LTP group shows a slight attenuation of latent inhibition with respect to the normal latent inhibition group but a strong retardation of acquisition with respect to the LTP control group. Finally, when increases and decreases in LTP are blocked, latent inhibition disappears because CS preexposure cannot decrease the initial value of incentive motivation.

Blocking

Experimental data. In blocking, an animal is first conditioned to CS_1, and this training is followed by conditioning to a compound consisting of CS_1 and a second stimulus CS_2. This procedure results in a weaker conditioning to CS_2 than it would attain if paired separately with the US. Solomon (1977) found that HL disrupted blocking of the rabbit NM response, and Rickert, Bent, Lane, and French (1978) found impairment in a blocking paradigm in rats. In contrast to these findings, Garrud et al. (1984) found that blocking was not affected by HL.

No data is available on the effect of LTP induction or LTP blockade on blocking.

Computer simulations. Figure 12 illustrates how the model describes blocking and shows sensory representations X_{11} and X_{21} in the second phase of blocking, after 10 CS–US trials. In the first phase of blocking, CS_1 is paired with the US, and associations V_1 and Z_1 are created. During the second phase of blocking in the normal case, incentive motivation Z_1 enhances the value of X_{11} causing X_{11} to inhibit X_{21} and therefore preventing X_{21} from acquiring association with the US. In the HL case, blocking is absent because X_{11} does not inhibit

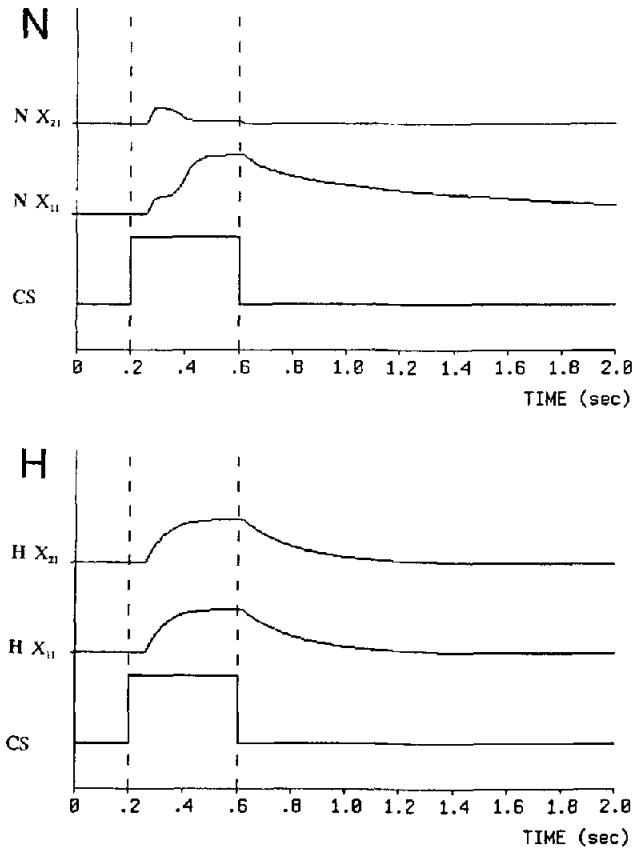

Figure 12. Effect of hippocampal lesions on the interaction between sensory representations during blocking. (Sensory representations of normal [N] and hippocampal-lesioned [H] animals generated by CS_1 and CS_2 after 10 reinforced CS_1 trials. In the normal case, X_{11} is enhanced by previous training and inhibits X_{21} thereby blocking its association with the unconditioned stimulus. In the H case, both X_{11} and X_{21} are independent, and therefore blocking is absent.)

X_{21} and therefore X_{21} is able to accrue the same association with the US, that it would have accrued in the absence of X_{11}.

Figure 13 shows peak CR amplitude after 10 CS_1–CS_2 acquisition trials that followed 10 CS_1 acquisition trials for normal, HL, LTP, and LTP blockade groups. Simulated training consisted of 400-ms CSs, a 50-ms US, and a 400-ms ISI. Figure 13 shows that the model simulated blocking in the normal case because the CR for the CS_2 was smaller in the experimental condition than in the control condition, in which CS_1 and CS_2 were paired together with the US during 10 trials (overshadowing in Figure 15). Consistent with Rickert et al. (1978) and Solomon (1977), simulations show that HL eliminates blocking.

Interestingly, the model predicts that LTP induction and LTP blockade are similar to HL in that they also eliminate blocking. In the case of LTP induction, blocking is prevented because both CSs have a strong initial incentive motivation and CS_1 cannot inhibit CS_2. In the case of LTP blockade, blocking is prevented because CS_1 does not increase its incentive motivation during the first experimental phase, and therefore its sensory representation cannot inhibit the sensory representation of CS_2 in the second phase.

Overshadowing

Experimental data. In overshadowing, an animal is conditioned to a compound consisting of CS_1 and CS_2. This procedure results in a weaker conditioning to CS_1 and CS_2 than they would independently achieve. Rickert, Lorden, Dawson, Smyly, and Callahan (1979) and Schmajuk, Spear, and Isaacson (1983) found that overshadowing is disrupted in rats with HL. In contrast to these findings, Garrud et al., (1984) and Solomon (1977) found that overshadowing was not affected by HL.

No data is available on the effect of LTP induction or LTP blockade on overshadowing.

Computer simulations. Figure 14 illustrates how the network describes overshadowing. When CS_1 and CS_2 are paired with the US, competition between X_{11} and X_{21} reduces X_{11} and X_{21} thereby reducing the rate of association of CS_1 and CS_2 with the US. Figure 14 shows sensory representations X_{11} and X_{21} in a trial in which CS_1 and CS_2 are presented together. In the normal case, overshadowing is produced because sensory representations X_{11} and X_{21} are smaller than when each CS is presented separately (see Figure 7C) and therefore they accrue less association with the US. As Figure 14 illustrates, overshadowing is absent in the HL case because X_{11} and X_{21} do not inhibit each other and therefore both are able to accrue the same V_i that they would have accrued in the absence of the other CS.

Figure 15 shows peak CR amplitude after 10 CS_1–CS_2 acquisition trials for normal, HL, LTP, and LTP blockade groups. Simulated training consisted of 400-ms CSs, a 50-ms US, and a 400-ms ISI. In the normal case, the CR elicited by CS_1 is smaller than CRs generated by CS_1 when it had been reinforced alone (i.e., the model yielded overshadowing in the normal case). Figure 15 shows that HL impairs overshadowing. These results are in agreement with Rickert et al.'s (1979) and Schmajuk et al.'s (1983) data showing that overshadowing is impaired by HL. In the LTP induction group, increased incentive motivation facilitates learning in the overshadowing and control groups, but overshadowing is still present because the phenomenon depends on the competition between sensory representations, which remains intact. Finally, LTP blockade affects overshadowing only slightly because of the unaltered competition between sensory representations.

Discrimination Acquisition and Reversal

Experimental data. In a discrimination paradigm, reinforced trials with CS_1 are alternated with nonreinforced trials with a second CS_2. During reversal, the original nonreinforced CS_2 is reinforced, whereas the CS_1 reinforced in the first phase is presented without the US.

The effect of HL on discrimination acquisition and reversal has been studied in the NM and eyelid preparations in the rabbit. Buchanan and Powell (1982) examined the effect of

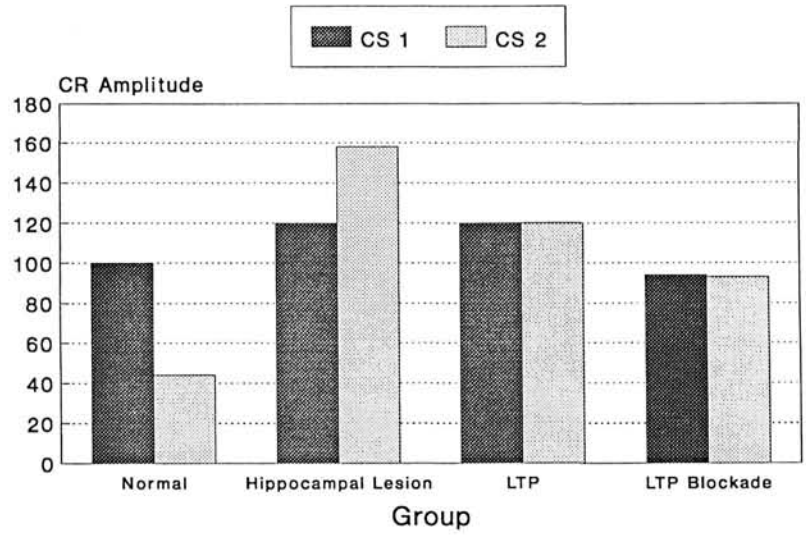

Figure 13. Effect of different hippocampal manipulations on blocking. (Peak conditioned response [CR] amplitude for normal, hippocampal lesion, long-term potentiation [LTP], and LTP blockade cases evoked by CS_2 after 10 reinforced CS_1–CS_2 trials and after 10 reinforced CS_1 trials. Peak CR amplitude is expressed as a percentage of the peak CR to CS_1 of normal animals after 10 reinforced CS_1 trials.)

HL on acquisition and reversal of eyeblink discrimination in rabbits. HL slightly impairs acquisition of discrimination and severely disrupts its reversal by showing an increased responding to CS−. Berger and Orr (1983) contrasted HL and control rabbits in two-tone differential conditioning and reversal of the rabbit NM response. Although HL does not affect initial differential conditioning, these animals are incapable of suppressing CRs to the original CS+ after it assumes the role of CS−. This is true even after extended training. Similar results were recently reported by Weikart and Berger (1986) in a tone–light discrimination reversal learning paradigm, suggesting that deficits in two-tone reversal learning after HL are not due to increased within-modality generalization to the tone CS serving as CS+ and CS−. Port, Romano, and Patterson (1986) found that HL impairs the reversal learning of a stimulus duration discrimination paradigm. In addition, Berger, Weikart, Bassett, and Orr (1986) found that lesions of the retrosplenial cortex, which connects the hippocampus to the cerebellar region, produce deficits in reversal learning of the rabbit NM response.

Berger (1984) found that entorhinal cortex stimulation that produced LTP in the perforant path–granule cell synapses increased the rate of acquisition of a two-tone classical discrimination of the rabbit NM response. Robinson et al. (1989) showed that kindling of the hippocampal perforant path–dentate gyrus projection (which induces LTP) facilitates discrimination acquisition but impairs discrimination reversal of the rabbit NM response.

Computer simulations. Figure 16 (top panel) shows simulations of discrimination acquisition for normal, HL, LTP, and LTP blockade groups. During discrimination acquisition, five reinforced CS_1–US trials alternate with five nonreinforced CS_2 trials. CS duration was 850 ms, US duration was 50 ms, and ISI was 800 ms. Figure 16 (top panel) shows similar discrimination acquisition in normal and HL cases. This result agrees with results obtained by Berger and Orr (1983), Berger et al. (1986), Port, Romano, and Patterson (1986), and Weikart and Orr (1986). Figure 16 also shows that discrimination acquisition is facilitated in the LTP group because of the increased incentive motivation. This result is in agreement with experimental data obtained by Berger (1984) and Robinson et al. (1989). Finally, Figure 16 (top panel) shows that LTP blockade weakly impairs discrimination acquisition.

Figure 16 (bottom panel) shows simulations of a discrimination reversal paradigm. During reversal, the original nonreinforced CS_2 is reinforced for three trials and these trials alternate with three nonreinforced CS_1 trials. CS duration was 850 ms, US duration was 50 ms, and ISI was 800 ms. Figure 16 (bottom panel) shows a slightly impaired discrimination reversal in the HL case. This result is in disagreement with results obtained by Berger and Orr (1983), Berger et al. (1986), Buchanan and Powell (1982), Port, Romano, and Patterson (1986), and Weikart and Orr (1986) that show a robust impairment due to the absence of extinction of the CS_1–US association. In agreement with experimental data obtained by Robinson et al. (1989), Figure 16 (bottom panel) shows that discrimination reversal might be retarded in the LTP group because the extinction of the CS_1–US association is slower in the LTP than in the normal group. Finally, Figure 16 (bottom panel) predicts that LTP blockade does not affect discrimination reversal.

Secondary Reinforcement

Experimental data. In secondary reinforcement, a CS_1 associated with the US acts as a reinforcer for a second CS_2.

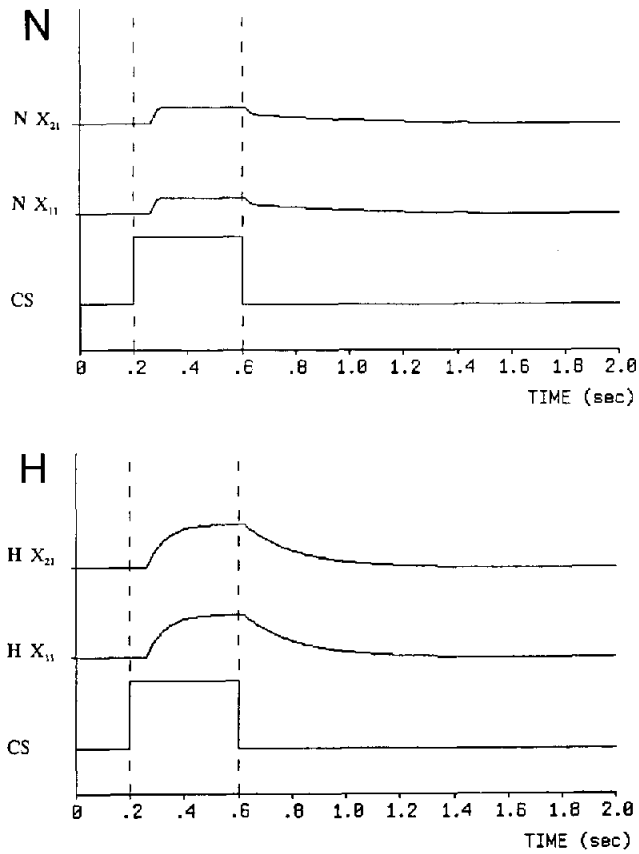

Figure 14. Effect of hippocampal lesions on the interaction between sensory representations during overshadowing. (Sensory representations of normal [N] and hippocampal-lesioned [H] animals generated by CS_1 and CS_2. In the normal case, X_{11} and X_{21} inhibit each other, thereby achieving less association with the unconditioned stimulus than when presented separately. In the H case, both X_{11} and X_{21} are independent, and therefore overshadowing is absent.)

To our knowledge, the effects of hippocampal manipulations have not been explored in a secondary reinforcement paradigm.

Computer simulations. Figure 17 shows simulations of a secondary reinforcement paradigm for normal, HL, LTP, and LTP blockade groups. During secondary reinforcement, 40 reinforced CS_1–US trials alternate with 40 CS_2–CS_1 trials. In the normal case, CS_1 increases its incentive motivation association during reinforced trials. When presented with CS_2 on the nonreinforced trials, CS_1 blocks CS_2 (see Figure 12), and therefore, CS_1 undergoes some extinction and CS_2 acquires some association with the drive representation activated by CS_1. The model predicts that secondary reinforcement is facilitated by HL because the conditioned reinforcer CS_1 does not block CS_2. Secondary reinforcement is impaired in the LTP group because CS_1 strongly blocks CS_2.

In the LTP blockade case, CS_1 gains a stronger association, and CS_2 gains a weaker association, with the drive representation than in the normal case. When LTP is prevented, CS_1 and CS_2 sensory representations overshadow each other (see Figure 14), and therefore, CS_1 undergoes less extinction than in the normal case, and CS_2 acquires less association, with the drive representation now only weakly activated by CS_1.

Discussion

This article introduces the STM regulation hypothesis of hippocampal function based on Grossberg's (1975) network. Based on the STM regulation hypothesis, nodes and connections in Grossberg's network are mapped, first, onto regional hippocampal–cerebellar circuits and, second, on a three-dimensional description of the hippocampal circuitry. According to the STM regulation hypothesis, the role of the hippocampus in classical conditioning is to regulate STM stored in the form of neural activity. Therefore, hippocampal lesions affect those paradigms that require a precise STM regulation. From the STM regulation hypothesis perspective, hippocampal LTP is the substrate for storing incentive motivations in LTM. Accordingly, equations describing changes in incentive motivation associations in the network are also able to describe empirical results regarding LTP. Behavior-related hippocampal neural activity reflects information about the drive representation that is needed to enhance relevant CSs through incentive motivation.

Mapping the Network Onto the Brain Circuitry

The present study offers a "top-down" approach to hippocampal function: It first portrays a neural network that describes associative learning and then proposes a plausible mapping of the network onto the brain circuitry.

The advantage of a top-down approach, clearly demonstrated in the present article, is that it can organize a large amount of—otherwise seemingly conflicting—data into the framework of a functional theory. In contrast, "bottom-up" approaches have serious difficulties in their attempt to derive the functional meaning of complex brain circuits from neurophysiological and anatomical information. For instance, so far it had been impossible to understand the functional significance of hippocampal LTP or CR-related neural activity in the hippocampus with a bottom-up approach. However, an important limitation of top-down approaches is that they might disregard some aspects of the brain circuitry (see *Mapping the network onto intrinsic hippocampal circuits*). Therefore, it is possible that an integration of a top-down strategy (providing a functional interpretation for components and connections) and a bottom-up method (contributing descriptions of these physiological components and connections) might overcome the inherent limitations of each technique.

Mapping the network onto regional hippocampal–cerebellar circuits. Because Grossberg's model is described as a neural architecture, the STM regulation hypothesis has been defined by mapping nodes and connections in Grossberg's neural network onto the brain circuitry. As described in *A Neural Model of Hippocampal–Cerebellar Interactions,* this mapping is constrained by the hippocampal–cerebellar connections, the behavioral effects of the induction of hippocampal LTP, and the firing characteristics of hippocampal pyramidal neurons.

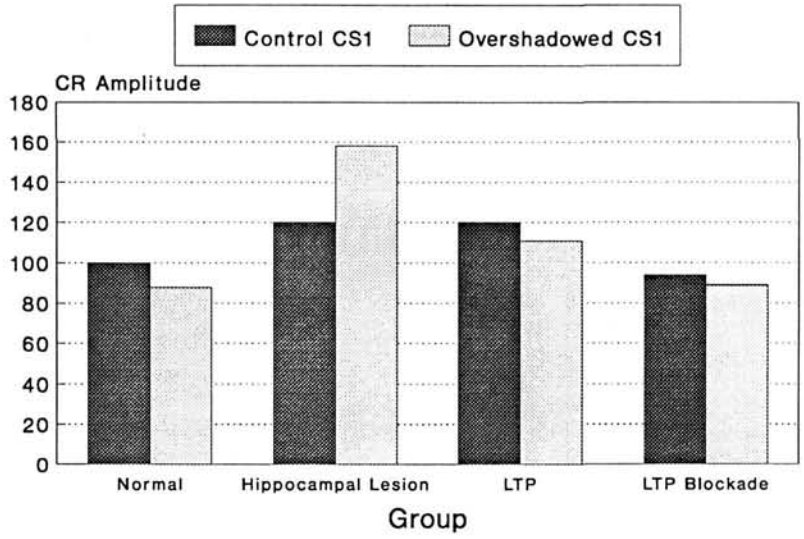

Figure 15. Effect of different hippocampal manipulations on overshadowing. (Peak conditioned response [CR] amplitude for normal, hippocampal lesion, long-term potentiation [LTP], and LTP blockade cases evoked by CS_1 after 10 reinforced CS_1–CS_2 trials. Peak CR amplitude is expressed as a percentage of the peak CR to CS_1 of normal animals after 10 reinforced CS_1 trials.)

In the Grossberg (1975) network, STM is modulated by three circuits: (a) an incentive motivation loop, (b) a competition loop, and (c) a self-excitation loop. The STM regulation hypothesis assumes that these loops are part of the hippocampus. The Grossberg network assumes two types of LTM: (a) conditioned reinforcement (X_{i1}–US) associations and (b) incentive motivation associations. The STM regulation hypothesis assumes that (a) X_{i1}–US associations are stored in cerebellar regions (in the rabbit NM preparation) and (b) incentive motivation associations are stored in the hippocampus in the form of LTP. Notably, rules describing changes in Z_i in the model are similar to those describing changes in hippocampal LTP. One important conjecture in the present article is that incentive motivation associations stored in the hippocampus change at a slower rate than X_{i1}–US associations stored in the cerebellum, and therefore the hippocampus has a memory of past X_{i1}–US associations even when they have been extinguished in the cerebellum and are no longer controlling behavior. This difference in the time scales of different LTM is used in our analysis to describe saving effects.

Because the model presented here is a system that describes classical conditioning in terms of the interaction between hippocampus and other brain regions, it establishes constraints on the models for those other brain regions. In the case of the cerebellum, it has been proposed that it implements learning models such as the Rescorla and Wagner (1972) model (e.g., Donegan, Gluck, & Thompson, 1988; Thompson, 1989) or the Sutton and Barto (1981) model (Moore & Blazis, 1989). According to these two models, classical conditioning paradigms such as blocking are independent of hippocampal function, whereas according to our model, blocking is dependent on the integrity of hippocampal function. Therefore, our model requires a cerebellar model that assumes independence among the sensory representations of different CSs.

Mapping the network onto intrinsic hippocampal circuits. Once the STM regulation hypothesis had been defined by mapping nodes and connections in Grossberg's neural network onto the regional hippocampal–cerebellar circuits, we attempted a more detailed mapping of the network onto the intrinsic circuit of the hippocampus. As described in *A Neural Model of the Hippocampus,* this mapping is constrained by the three-dimensional organization of the hippocampus, the distribution and properties of hippocampal LTP and the firing characteristics of hippocampal CA3, CA1, and granule neurons.

Figure 3 shows that one class of pyramidal cell population in CA3 receives sensory representations from the entorhinal cortex and helps to sustain these sensory representation activities through positive feedback loops. A second class of pyramidal cell population in CA3 associates CR-related inputs with sensory inputs from the entorhinal cortex and is part of incentive motivation loops. A third class of pyramidal cell population in CA1 is assumed to add sensory information from different rostrocaudal levels of the hippocampus and to be part of competition loops. Hippocampal outputs integrating positive feedback loops, incentive motivation loops, and competition loops regulate sensory representation activities in the pontine nuclei.

The neural network shown in Figure 3 ignores important hippocampal components and connections, such as septal inputs, basket cells, and recurrent collaterals in field CA3. Nevertheless, some of the functional properties of these elements are captured by the model. For instance, Robinson's (1986) findings that LTP induced in the rat dentate gyrus is enhanced by coactivation of septal and entorhinal inputs could be captured within the framework of the model by

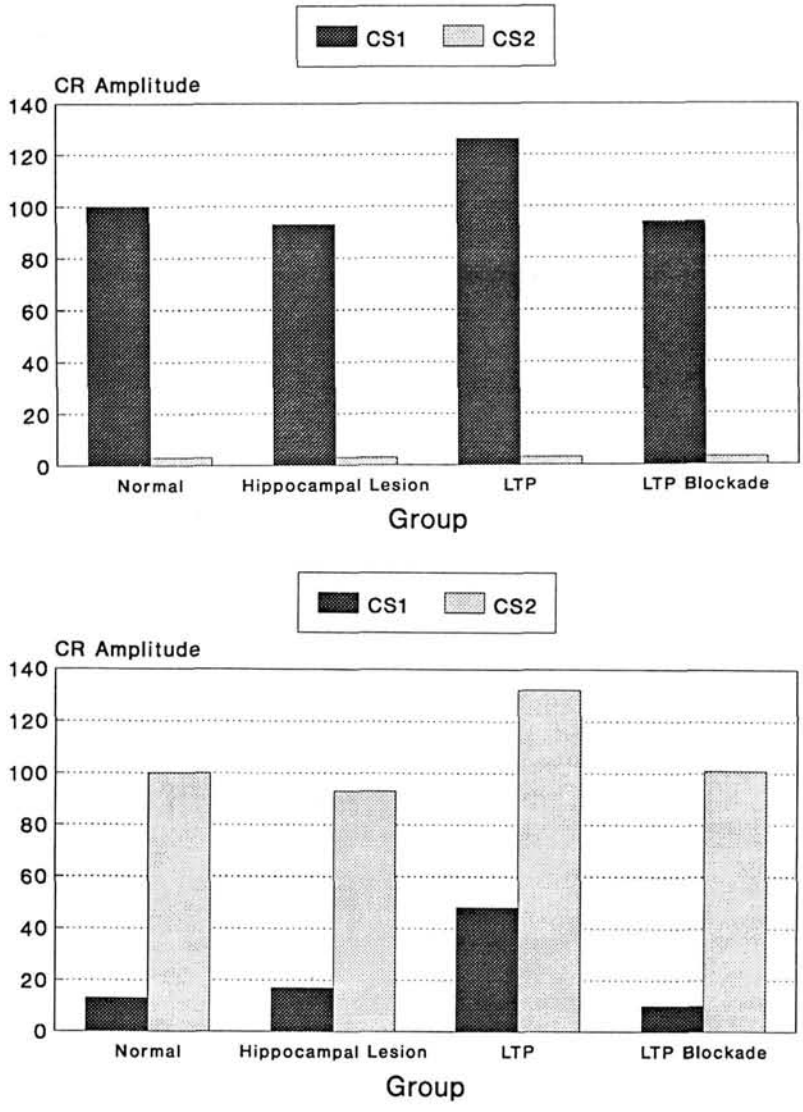

Figure 16. Effect of different hippocampal manipulations on discrimination. (Top panel: Discrimination acquisition. Peak conditioned response [CR] amplitude for normal, hippocampal lesion, long-term potentiation [LTP], and LTP blockade cases evoked by CS_1 and CS_2 after five reinforced CS_1 trials alternated with five nonreinforced CS_2 trials. Peak CR amplitude is expressed as a percentage of the peak CR to CS_1 of normal animals. Bottom panel: Discrimination reversal. Peak CR amplitude for normal, hippocampal lesion, LTP, and LTP blockade cases evoked by CS_1 and CS_2 after three nonreinforced CS_1 trials alternated with three reinforced CS_2 trials. Peak CR amplitude is expressed as a percentage of the peak CR to CS_2 of normal animals.)

assuming that the medial septal input is controlling the rate of change of the incentive motivation association (Z_i). Therefore, the effects of medial septal lesions would be equivalent to the effect of LTP blockade, which might reduce the rate of acquisition (see Figure 8). This suggestion is compatible with Berry and Thompson's (1979) data showing that lesions of the medial septum produce retardation of acquisition of classical conditioning. Also in the framework of the model, the inhibition exerted by basket cells on neighboring lamellas might mediate competition among sensory representations. Finally, recurrent collaterals in CA3 might mediate self-excitation of sensory representations.

Figure 3 shows both fixed and modifiable perforant path–CA3 synapses but only the fixed synapses connecting other hippocampal fields. As previously mentioned, in addition to the perforant path–CA3 plastic synapses where incentive motivation Z_i is assumed to be stored in the form of LTP, LTP has also been found in many other synapses. A possible role of LTP in the Schaffer collateral–CA1 synapses, perforant path–CA1 synapses, and mossy fiber–CA3 synapses is that

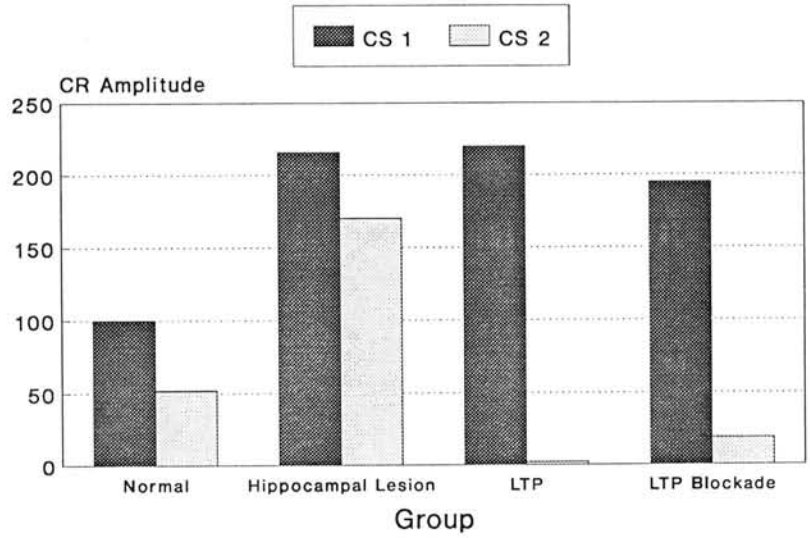

Figure 17. Effect of different hippocampal manipulations on secondary reinforcement. (Peak conditioned response [CR] amplitude for normal, hippocampal lesion, long-term potentiation [LTP], and LTP blockade cases evoked by CS_1 and CS_2 after 40 reinforced CS_1 trials alternated with 40 nonreinforced CS_1–CS_2 trials. Peak CR amplitude is expressed as a percentage of the peak CR to CS_1 of normal animals.)

of serving as an additional distributed storage for incentive motivation associations, Z_i.

Although Figure 3 shows a sensory representation input from the entorhinal cortex that reaches granule cells in the dentate gyrus, and the connection strength of this input seems to be endogenously potentiated during classical conditioning (Weisz et al., 1984), the Grossberg model does not capture this presumably important plastic change in perforant path–dentate gyrus synapses. It is possible that perforant path–dentate gyrus synapses store associations between sensory representations and the theta rhythm. Because the theta rhythm seems to be correlated with unexpected environmental events (see Schmajuk & Moore, 1988), the association between sensory representations and the theta rhythm may serve to enhance the STM of those CSs active at the time when novel events occur. These putative associations might supplement the incentive motivation associations (Z_i) introduced in this article.

In summary, because the neural network shown in Figure 3 overlooks several hippocampal components and connections, the mapping of the network onto the intrinsic hippocampal circuit offers only a tentative description of the specific function of each hippocampal field.

Regardless of the previously mentioned limitations, because the mapping of the Grossberg model onto the hippocampal circuit incorporates the concept of the three-dimensional organization of the hippocampus, it becomes an appealing alternative to previous lamellar models of the hippocampus (McNaughton & Morris, 1987; Rolls, 1987; Schmajuk & Moore, 1988). These models proposed that heteroassociative networks (Kohonen, 1977) represent the lamellar arrangement of regions CA1 and CA3. Schmajuk and Moore (1988) showed that, under the assumption that such heteroassociative networks store CS–CS associations in the form of LTP, the model cannot describe correctly the effect of LTP induction on the acquisition of a classical discrimination as described by Berger (1984) and Robinson et al. (1989). In contrast, the STM regulation hypothesis successfully describes this experimental result.

Simulation Results

Table 2 summarizes the results of the simulation experiments for HL, LTP, and LTP blockade simulations. Under the STM regulation hypothesis, the model is able to describe the effect of HL on delay conditioning, trace conditioning, extinction, acquisition series, latent inhibition, blocking, overshadowing, and discrimination acquisition and the effect of LTP induction on discrimination acquisition and reversal. Under the STM regulation hypothesis, the model has difficulty simulating the effect of HL on extinction series and discrimination reversal.

According to the model, HL impairs classical conditioning paradigms that involve more than one CS (e.g., blocking). In the case of a CS presented in isolation, the model specifies the conditions under which acquisition or extinction paradigms are impaired, unaffected, or even facilitated. The present model replaces the notion that trace conditioning or extinction are or are not affected by HL, by the concept that STM is more or less changed under different experimental parameters. Therefore, the model offers simple principles that explain seemingly conflicting data.

In terms of the STM regulation hypothesis, LTP induction indiscriminately increases incentive motivation associations of every CS. In consequence, although LTP induction sometimes facilitates those paradigms in which a CS is individ-

Table 2
Simulation of Grossberg's (1975) Model Under the STM Regulation Hypothesis Regarding Hippocampal Function, Compared With Experimental Results in Classical Conditioning

	Hippocampal lesions		LTP		LTP blockade	
Paradigm	Data	Model	Data	Model	Data	Model
Delay conditioning	+, 0	+, 0	?	+, 0	?	−, 0
Trace conditioning	0, −	+, 0, −	?	+, 0	?	−, 0
Extinction	0, −	0, −	?	0	?	0
Acquisition series	−	−	?	+	?	−
Extinction series	−	0 *	?	+	?	−
Latent inhibition	−	−	?	−	?	−
Blocking	−	−	?	−	?	−
Overshadowing	−, 0	−	?	−	?	−
Discrimination acquisition	0, 0	0	+	+	?	0
Discrimination reversal	−	0 *	−	−	?	−
Secondary reinforcement	?	+	?	−	?	−

Note. − = deficit; + = facilitation; 0 = no effect; ? = no available data; * = the model fails to describe accurately the experimental data.

ually reinforced (e.g., delay conditioning), it impairs those paradigms in which various CSs are simultaneously reinforced and their individual differences are important (e.g., blocking).

The STM regulation hypothesis proposes that LTP blockade indiscriminately prevents changes in incentive motivation associations of every CS. In consequence, LTP blockade impairs paradigms in which a CS is individually reinforced (e.g., delay conditioning) as well as those paradigms in which various CSs are simultaneously reinforced (e.g., blocking).

Although the present article concentrates only on classical conditioning, it is tempting to extend some of the predictions of the STM regulation hypothesis to spatial learning. As already mentioned, the STM regulation hypothesis suggests that HL, LTP induction, and LTP blockade impair paradigms in which several CSs are concurrently reinforced. In agreement with this suggestion, acquisition of place learning (a paradigm in which animals make use of multiple distal visual stimuli to find reward) is impaired by HL (Jarrard, 1983; Morris, Garrud, Rawlins, & O'Keefe, 1982), LTP induction (McNaughton, Barnes, Rao, Baldwin, & Rasmussen, 1986), and LTP blockade (Morris et al., 1986). Also in agreement with this view, acquisition of cue learning (a paradigm in which animals make use of only one stimuli to find reward) remains unaffected by HL (Jarrard, 1983; Morris et al., 1982).

Novel Predictions

The model provides novel predictions for the effect of HL, LTP induction, and LTP blockade. These predictions, listed in Table 2, are currently unexplored and constitute a challenge for experimentalists.

The model suggests that secondary reinforcement is facilitated by HL. Because incentive motivation associations (Z_i) are absent after HL, the model anticipates that savings effects are impaired by HL. The model also proposes that HL modifies acquisition of classical conditioning according to the combination of variables used in the experimental design (e.g., CS duration, CS intensity, ISI) rather than according to the type of paradigm (e.g., extinction, trace conditioning) tested. Therefore, the model implies that parametric studies of the effects of HL on acquisition and extinction of classical conditioning are needed.

The model also describes expected effects of LTP induction and blockade on delay conditioning, trace conditioning, extinction, acquisition–extinction series, latent inhibition, blocking, overshadowing, discrimination acquisition, and discrimination reversal. As in the HL case, some of the results might also depend on the experimental parameters.

Finally, the model predicts changes in neural activity recordings after different experimental manipulations. For instance, because of the lack of self-excitation, sensory representations are expected to be shorter in the HL case than in the normal case (see Figure 7). Because incentive motivation associations are increased by LTP induction, sensory representations are expected to be larger and longer in the LTP case than in the normal case. Also, in a blocking paradigm, the sensory representation of the blocker CS is anticipated to be larger than that of the blocked CS. In addition, in a overshadowing paradigm, the sensory representation of each CS is presumed to be smaller when both CSs are presented together than when they are presented separately. These predictions can be easily evaluated by recording neural activity in the pontine nucleus.

Comparison With Other Attentional Models of Hippocampal Function in Classical Conditioning

The present results support an attentional view of hippocampal function. As mentioned before, hippocampal function has been described as the modulation of the level of processing assigned to environmental stimuli in the context of the MSS (Schmajuk & Moore, 1989) and the SPH (Schmajuk, 1989; Schmajuk & Moore, 1988) attentional models. In the context of the MSS model, the tuning-out hypothesis assumes that the hippocampus compares how well different

CSs predict the US, reducing the associative rates (α_i) of nonreliable CSs. In the context of the SPH model, the aggregate prediction hypothesis assumes that the hippocampus computes the aggregate prediction of the US. Once the US is well predicted by one CS, processing of all other CSs is inhibited, thereby precluding them from gaining association with the US. Under the STM regulation hypothesis, variables in the Grossberg model that are assumed to be computed in the hippocampus are similar to hippocampal-related variables in the MSS and the SPH models: Associative rate α_i in the MSS model is similar to the term Z_i in the Grossberg model, and aggregate prediction $\Sigma_j B_j^k$ in the SPH model corresponds to the term $\Sigma_{j \neq i} X_{j1}$ in the Grossberg model. Therefore, in some respects the model offered in the present study captures some of the features of previous models.

When compared with the MSS and the SPH models, Grossberg's (1975) model under the STM hypothesis provides a similar number of correct predictions for the paradigms shown in Table 2. In contrast to the MSS model, Grossberg's model under the STM hypothesis incorrectly predicts the outcome of a mutual overshadowing experiment in HL animals. In contrast to the SPH model, Grossberg's model under the STM hypothesis incorrectly predicts the outcome of discrimination reversal in HL animals. In all other paradigms, all three models correctly predict the effect of HL on classical conditioning. However, under the STM regulation hypothesis, Grossberg's model is the only one to provide a correct description of the effect of LTP induction on discrimination acquisition. In addition, Grossberg's is the only one that describes the interaction between CS duration and ISI on the acquisition of classical conditioning.

Finally, although both the MSS and the SPH models describe more classical conditioning paradigms than Grossberg's (1975) model, the latter can be integrated to other neural networks that substantially extend its domain of application (see Grossberg & Schmajuk, 1987). This extended domain would allow the application of the model to the description of the effect of hippocampal manipulations on conditioned inhibition, which is not affected by HL (Solomon, 1977); differential conditioning, which is impaired by HL (Micco & Schwartz, 1972); feature-positive discrimination, which is impaired by HL (Loechner & Weisz, 1987); and sensory preconditioning, which is impaired by HL (Port & Patterson, 1984).

Conclusion

In the context of Grossberg's (1975) model, the present article proposes that the hippocampus regulates the contents of a limited-capacity STM by controlling incentive motivation, self-excitation, and competition among sensory representations. The STM regulation hypothesis provides a framework for understanding information processing and storage in the hippocampus and the interactions between the hippocampus and cerebellum during classical conditioning. The network yields correct descriptions of many experimental results, offers principles that help to understand seemingly conflicting data, and advances numerous novel and testable predictions.

References

Ali, S. M., Bullock, S., & Rose, S. P. R. (1988). Protein kinase C inhibitors prevent long-term memory formation in the one-day old chick. *Neuroscience Research Communications, 3,* 133–140.

Amaral, D. G., & Witter, M. P. (1989). The three-dimensional organization of the hippocampal formation: A review of anatomical data. *Neuroscience, 31,* 571–591.

Andersen, P., Bliss, T. V. P., & Skrede, K. K. (1971). Unit analysis of the hippocampal populations spikes. *Experimental Brain Research, 13,* 208–221.

Berger, T. W. (1984). Long-term potentiation of hippocampal synaptic transmission affects rate of behavioral learning. *Science, 224,* 627–630.

Berger, T. W., Alger, B., & Thompson, R. F. (1976). Neuronal substrate of classical conditioning in the hippocampus. *Science, 192,* 483–485.

Berger, T. W., Bassett, J. L., & Weikart, C. (1985, November). *Hippocampal–cerebellar interactions during classical conditioning.* Paper presented at the 26th annual meeting of The Psychonomic Society, Boston, MA.

Berger, T. W., Clark, G. A., & Thompson, R. F. (1980). Learning-dependent neuronal responses recorded from limbic system brain structures during classical conditioning. *Physiological Psychology, 8,* 155–167.

Berger, T. W., & Orr, W. B. (1983). Hippocampectomy selectively disrupts discrimination reversal conditioning of the rabbit nictitating membrane response. *Behavioural Brain Research, 8,* 49–68.

Berger, T. W., Rinaldi, P. C., Weisz, D. J., & Thompson, R. F. (1983). Single-unit analysis of different hippocampal cell types during classical conditioning of rabbit nictitating membrane response. *Journal of Neurophysiology, 50,* 1197–1219.

Berger, T. W., Swanson, G. W., Milner, T. A., Lynch, G. S., & Thompson, R. F. (1980). Reciprocal anatomical connections between hippocampus and subiculum in the rabbit: Evidence for subicular innervation of regio superior. *Brain Research, 183,* 265–276.

Berger, T. W., & Thompson, R. F. (1978a). Neuronal plasticity in the limbic system during classical conditioning of the rabbit nictitating membrane response: I. The hippocampus. *Brain Research, 145,* 323–346.

Berger, T. W., & Thompson, R. F. (1978b). Neuronal plasticity in the limbic system during classical conditioning of the rabbit nictitating membrane response: II. Septum and mammillary bodies. *Brain Research, 156,* 293–314.

Berger, T. W., & Thompson, R. F. (1982). Hippocampal cellular plasticity during extinction of classically conditioned nictitating membrane behavior. *Behavioural Brain Research, 4,* 63–76.

Berger, T. W., Weikart, C. L., Bassett, J. L., & Orr, E. B. (1986). Lesions of the retrosplenial cortex produce deficits in reversal learning of the rabbit nictitating membrane response: Implications for potential interactions between hippocampal and cerebellar brain systems. *Behavioral Neuroscience, 100,* 802–809.

Berry, S. D., & Thompson, R. F. (1979). Medial septal lesions retard classical conditioning of the nictitating membrane response in rabbits. *Science, 205,* 209–211.

Bliss, T. V. P., & Lynch, M. A. (1988). Long-term potentiation of synaptic transmission in the hippocampus: Properties and mechanisms. In P. W. Landfield & S. A. Deadwyler (Eds.), *Long-term potentiation: From biophysics to behavior* (pp. 3–72). New York: Alan R. Liss.

Buchanan, S. L., & Powell, D. A. (1982). Cingulate cortex: Its role in Pavlovian conditioning. *Journal of Comparative and Physiological Psychology, 96,* 755–774.

Clark, G. A., McCormick, D. A., Lavond, D. G., & Thompson, R. F. (1984). Effects of lesions of cerebellar nuclei on conditioned behavioral and hippocampal neuronal responses. *Brain Research, 291,* 125–136.

Disterhoft, J. F., Coulter, D. A., & Alkon, D. L. (1986). Enhancement of synaptic potentials in rabbit CA1 pyramidal neurons following classical conditioning. *Proceedings of the National Academy of Sciences USA, 83,* 2733–2737.

Disterhoft, J. F., Coulter, D. A., & Alkon, D. L. (1988). Conditioning-specific biophysical alterations in rabbit hippocampus. In C. Woody, D. Alkon, & J. McGaugh (Eds.), *Cellular mechanisms of conditioning and behavioral plasticity* (pp. 89–104). New York: Plenum Press.

Disterhoft, J. F., Golden, D. T., Read, H. L. Coulter, D. A., & Alkon, D. L. (1988). AHP reductions in rabbit hippocampal neurons during conditioning correlate with acquisition of the learned response. *Brain Research, 462,* 118–125.

Donegan, N. H., Gluck, M. A., & Thompson, R. F. (1988). Interpreting behavioral and biological models of classical conditioning. In R. D. Hawkins & G. H. Bower (Eds.), *Computational models of learning in simple neural systems* (pp. 109–156). New York: Academic Press.

Garrud, P., Rawlins, J. N. P., Mackintosh, N. J., Goodal, G., Cotton, M. M., & Feldon, J. (1984). Successful overshadowing and blocking in hippocampectomized rats. *Behavioural Brain Research, 12,* 39–53.

Gormezano, I., Kehoe, E. J., & Marshall, B. S. (1983). Twenty years of classical conditioning research with the rabbit. *Progress in Psychobiology and Physiological Psychology, 10,* 197–275.

Grossberg, S. (1975). A neural model of attention, reinforcement, and discrimination learning. *International Review of Neurobiology, 18,* 263–327.

Grossberg, S., & Levine, D. S. (1987). Neural dynamics of attentionally modulated Pavlovian conditioning: Blocking, interstimulus interval, and secondary reinforcement. *Applied Optics, 26,* 5015–5030.

Grossberg, S., & Schmajuk, N. A. (1987). Neural dynamics of Pavlovian conditioning: Conditioned reinforcement, habituation, and opponent processing. *Psychobiology, 15,* 195–240.

Hebb, D. (1949). *The organization of behavior.* New York: Wiley.

Hoechler, F. K., & Thompson, R. F. (1980). Effect of the interstimulus (CS–UCS) interval on hippocampal unit activity during classical conditioning of the nictitating membrane response of the rabbit (*Oryctolagus cuniculus*). *Journal of Comparative and Physiological Psychology, 7,* 201–215.

Ito, M. (1984). *The cerebellum and neural control.* New York: Raven Press.

James, G. O., Hardiman, M. J., & Yeo, C. H. (1987). Hippocampal lesions and trace conditioning in the rabbit. *Behavioural Brain Research, 23,* 109–116.

Jarrard, L. E. (1983). Selective hippocampal lesions and behavior: Effects of kainic acid lesions on performance of place and cue tasks. *Behavioral Neuroscience, 97,* 873–889.

Kaye, H., & Pearce, J. M. (1987a). Hippocampal lesions attenuate latent inhibition and the decline of the orienting response in rats. *Quarterly Journal of Experimental Psychology, 39B,* 107–125.

Kaye, H., & Pearce, J. M. (1987b). Hippocampal lesions attenuate latent inhibition of a CS and of a neutral stimulus. *Psychobiology, 15,* 293–299.

Kelso, S. R., Ganong, A. H., & Brown, T. H. (1986). Hebbian synapses in hippocampus. *Proceedings of the National Academy of Science USA, 83,* 5326–5330.

Kononen, T. (1977). *Associative memory: A system-theoretical approach.* New York: Springer-Verlag.

Levy, W. B., Brassel, S. E., & Moore, S. D. (1983). Partial quantification of the associative synaptic learning rule of the dentate gyrus. *Neuroscience, 8,* 799–808.

Levy, W. B., & Steward, O. (1979). Synapses as associative memory elements in the hippocampal formation. *Brain Research, 175,* 233–245.

Loechner, K. J., & Weisz, D. J. (1987). Hippocampectomy and feature-positive discrimination. *Behavioural Brain Research, 26,* 63–73.

Lopez De Silva, F. H., Groenewegen, H. J., Holsheimer, J., Room, P., Witter, M. P., Van Groen, T., & Wadman, W. J. (1985). The hippocampus as a set of partially overlapping segments with a topographically organized system of inputs and outputs: The entorhinal cortex as a sensory gate, the medial septum as a gain-setting system, and the ventral striatum as a motor interface. In G. Buzsaki & C. H. Vanderwolf, *Electrical activity of the archicortex* (pp. 83–106). Budapest, Hungary: Akademiai Kiado.

LoTurco, J. J., Coulter, D. A., & Alkon, D. L. (1988). Enhancement of synaptic potentials in rabbit CA1 pyramidal neurons following classical conditioning. *Proceedings of the National Academy of Science USA, 85,* 1672–1676.

Lovinger, D. M., Wong, K. L., Murakami, K., & Routtenberg, A. (1987). Protein kinase C inhibitors eliminate hippocampal long-term potentiation. *Brain Research, 436,* 177–183.

MacFarland, D. J., Kostas, J., & Drew, W. G. (1978). Dorsal hippocampal lesions: Effects of preconditioning CS preexposure on flavor aversion. *Behavioral Biology, 2,* 398–404.

Mackintosh, N. J. (1975). A theory of attention: Variations in the associability of stimuli with reinforcer. *Psychological Review, 82,* 276–298.

McNaughton, B. L., Barnes, C. A., Rao, G., Baldwin, J., & Rasmussen, M. (1986). Long-term enhancement of hippocampal synaptic transmission and the acquisition of spatial information. *Journal of Neuroscience, 6,* 563–571.

McNaughton, B. L., & Morris, R. G. M. (1987). Hippocampal synaptic enhancement and information storage within a distributed memory system. *Trends in Neurosciences, 10,* 408–415.

Micco, D. J., & Schwartz, M. (1972). Effects of hippocampal lesions upon the developments of Pavlovian internal inhibition in rats. *Journal of Comparative and Physiological Psychology, 76,* 371–377.

Moore, J. W., & Blazis, D. E. J. (1989). Simulation of a classically conditioned response: A cerebellar neural network implementation of the Sutton-Barto-Desmond model. In J. H. Byrne & W. O. Berry (Eds.), *Neural models of plasticity* (pp. 187–207). San Diego, CA: Academic Press.

Moore, J. W., & Stickney, K. J. (1980). Formation of attentional–associative networks in real time: Role of the hippocampus and implications for conditioning. *Physiological Psychology, 8,* 207–217.

Moore, J. W., & Stickney, K. J. (1982). Goal tracking in attentional-associative networks: Spatial learning and the hippocampus. *Physiological Psychology, 10,* 202–208.

Morris, R. G. M., Anderson, E., Lynch, G. S., & Baudry, M. (1986). Selective impairment of learning and blockade of long-term potentiation by an *N*-methyl-D-aspartate receptor antagonist, AP5. *Nature, 319,* 774–776.

Morris, R. G. M., Garrud, P., Rawlins, J. N. P., & O'Keefe, J. (1982). Place navigation impaired in rats with hippocampal lesions. *Nature, 297,* 681–683.

Moyer, J. R., Deyo, R. A., & Disterhoft, J. F. (1988). Effects of hippocampal lesions on acquisition and extinction of trace eyeblink response in rabbits. *Society for Neuroscience Abstracts, 14,* 233.

Moyer, J. R., Deyo, R. A., & Disterhoft, J. F. (1990). Hippocampectomy disrupts trace eye-blink conditioning in rabbits. *Behavioral Neuroscience, 104,* 243–252.

Pearce, J. M., & Hall, G. (1980). A model for Pavlovian learning: Variations in the effectiveness of conditioned but not of unconditioned stimuli. *Psychological Review, 87,* 532–552.

Port, R. L., Mikhail, A. A., & Patterson, M. M. (1985). Differential effects of hippocampectomy on classically conditioned rabbit nictitating membrane response related to interstimulus interval. *Behavioral Neuroscience, 99,* 200–208.

Port, R. L., & Patterson, M. M. (1984). Fimbrial lesions and sensory preconditioning. *Behavioral Neuroscience, 98,* 584–589.

Port, R. L., Romano, A. G., & Patterson, M. M. (1986). Stimulus duration discrimination in the rabbit: Effects of hippocampectomy on discrimination and reversal learning. *Physiological Psychology, 14,* 124–129.

Port, R. L., Romano, A. G., Steinmetz, J. E., Mikhail, A. A., & Patterson, M. M. (1986). Retention and acquisition of classical trace conditioned responses by rabbits with hippocampal lesions. *Behavioral Neuroscience, 100,* 745–752.

Rescorla, R. A., & Wagner, A. R. (1972). A theory of Pavlovian conditioning: Variation in the effectiveness of reinforcement and non-reinforcement. In A. H. Black & W. F. Prokasy (Eds.), *Classical conditioning II: Theory and research* (pp. 64--99). New York: Appleton-Century-Crofts.

Rickert, E. J., Bent, T. L., Lane, P., & French, J. (1978). Hippocampectomy and the attenuation of blocking. *Behavioral Biology, 22,* 147–160.

Rickert, E. J., Lorden, J. F., Dawson, R., Smyly, E., & Callahan, M. F. (1979). Stimulus processing and stimulus selection in rats with hippocampal lesions. *Behavioral and Neural Biology, 27,* 454–465.

Robinson, G. B. (1986). Enhanced long-term potentiation induced in rat dentate gyrus by coactivation of septal and entorhinal inputs. *Brain Research, 379,* 56–62.

Robinson, G. B., Port, R. L., Berger, T. W. (1989). Kindling facilitates acquisition of discriminative responding but disrupts reversal learning of the rabbit nictitating membrane response. *Behavioural Brain Research, 31,* 279–283.

Rolls, E. T. (1987). Information representation, processing, and storage in the brain: Analysis at the single neuron level. In J. P. Changeaux & M. Konishi (Eds.), *The neural and molecular bases of learning* (pp. 240–265). New York: Wiley.

Ruth, R. E., Collier, T. J., & Routtenberg, A. (1982). Topography between the entorhinal cortex and the dentate septotemporal axis in rats: I. Medial and intermediate entorhinal projecting cells. *Journal of Comparative Neurology, 209,* 69–78.

Ruth, R. E., Collier, T. J., & Routtenberg, A. (1988). Topographical relationship between the entorhinal cortex and the septotemporal axis of the dentate gyrus in rats: II. Cells projecting from lateral entorhinal subdivisions. *Journal of Comparative Neurology, 270,* 506–516.

Scavio, M. J., Ross, R. T., & McLeod, L. M. (1983). Perseveration of associative strength in the rabbit nictitating membrane response conditioning. *Animal Learning and Behavior, 11,* 91–94.

Schmajuk, N. A. (1984). A model of the effects of hippocampal lesions on Pavlovian conditioning. *Society for Neuroscience, Abstracts 10,* 124.

Schmajuk, N. A. (1985). Psychological theories of hippocampal function. *Physiological Psychology, 12,* 166–183.

Schmajuk, N. A. (1986). *Real-time attentional models for classical conditioning and the hippocampus.* Unpublished doctoral dissertation, University of Massachusetts.

Schmajuk, N. A. (1989). The hippocampus and the control of information storage in the brain. In M. Arbib & S. I. Amari (Eds.), *Dynamic interactions in neural networks: Models and data* (pp. 53–72). New York: Springer Verlag.

Schmajuk, N. A. (1990). Role of the hippocampus in temporal and spatial navigation. *Behavioural Brain Research, 39,* 205–229.

Schmajuk, N. A., & DiCarlo, J. J. (1990). Neural dynamics of hippocampal modulation of classical conditioning. In M. Commons, S. Grossberg, & J. E. R. Staddon (Eds.), *Neural network models of conditioning and action* (pp. 149–180). Hillsdale, NJ: Erlbaum.

Schmajuk, N. A., & Moore, J. W. (1985). Real-time attentional models for classical conditioning and the hippocampus. *Physiological Psychology, 13,* 278–290.

Schmajuk, N. A., & Moore, J. W. (1988). The hippocampus and the classically conditioned nictitating membrane response: A real-time attentional–associative model. *Psychobiology, 46,* 20–35.

Schmajuk, N. A., & Moore, J. W. (1989). Effects of hippocampal manipulations on the classically conditioned nictitating membrane response: Simulations by an attentional–associative model. *Behavioural Brain Research, 32,* 173–189.

Schmajuk, N. A., Spear, N. E., & Isaacson, R. L. (1983). Absence of overshadowing in rats with hippocampal lesions. *Physiological Psychology, 11,* 59–62.

Schmaltz, L. W., & Theios, J. (1972). Acquisition and extinction of a classically conditioned response in hippocampectomized rabbits (*Oryctolagus cuniculus*). *Journal of Comparative and Physiological Psychology, 789,* 328–333.

Semple-Rowland, S. L., Bassett, J. L., & Berger, T. W. (1981). Subicular projections to retrosplenial cortex in the rabbit. *Society for Neurosciences Abstracts, 7,* 886.

Shepherd, G. M. (1979). *The synaptic organization of the brain,* New York: Oxford University Press.

Solomon, P. R. (1977). Role of the hippocampus in blocking and conditioned inhibition of rabbit's nictitating membrane response. *Journal of Comparative and Physiological Psychology, 91,* 407–417.

Solomon, P. R., & Moore, J. W. (1975). Latent inhibition and stimulus generalization of the classically conditioned nictitating membrane response in rabbits (*Oryctolagus cuniculus*) following dorsal hippocampal ablation. *Journal of Comparative and Physiological Psychology, 89,* 1192–1203.

Solomon, P. R., Vander Schaaf, E. R., Thompson, R. F., & Weisz, D. J. (1986). Hippocampus and trace conditioning of the rabbit's classically conditioned nictitating membrane response. *Behavioral Neuroscience, 100,* 729–744.

Squire, L. R., Shimamura, A. P., & Amaral, D. G. (1989). Memory and the hippocampus. In J. H. Byrne & W. Berry (Eds.), *Neural models of plasticity* (pp. 208–239). New York: Academic Press.

Stanton, P. K., & Sejnowski, T. J. (1989). Associative long-term depression in the hippocampus induced by hebbian covariance. *Nature, 339,* 215–218.

Steinmetz, J. E., Logan, C. G., & Thompson, R. F. (1988). Essential involvement of mossy fibers in projecting the CS to the cerebellum during classical conditioning. In C. Woody, D. Alkon, & J. McGaugh (Eds.), *Cellular mechanisms of conditioning and behavioral plasticity* (pp. 143–148). New York: Plenum Press.

Sutton, R. S., & Barto, A. G. (1981). Toward a modern theory of adaptive networks: Expectation and prediction. *Psychological Review, 88,* 135–170.

Thompson, R. F. (1986). The neurobiology of learning and memory. *Science, 233,* 941–947.

Thompson, R. F. (1989). Neural circuit for classical conditioning of the eyelid closure response. In J. H. Byrne & W. O. Berry (Eds.), *Neural models of plasticity* (pp. 160–177). San Diego, CA: Academic Press.

Vinogradova, O. S. (1975). Functional organization of the limbic system in the process of registration of information: Facts and hypothesis. In R. L. Isaacson & K. H. Pribram (Eds.), *The hippocampus* (pp. 3–69). New York: Plenum Press.

Weikart, C., & Berger, T. W. (1986). Hippocampal lesions disrupt classical conditioning of cross-modality reversal learning of the rabbit nictitating membrane response. *Behavioural Brain Research, 22,* 85–90.

Weikart, C., & Berger, T. W. (1986). Hippocampal lesions disrupt classical conditioning of cross-modality reversal learning of the rabbit nictitating membrane response. *Behavioural Brain Research, 22,* 85–90.

Weisendanger, R., & Weisendanger, M. (1982). The corticopontine system in the rat. *Journal of Comparative Neurology, 208,* 227–238.

Weisz, D. J., Clark, G. A., & Thompson, R. F. (1984). Increased responsivity of dentate granule cells during nictitating membrane response conditioning in rabbit. *Behavioural Brain Research, 12,* 145–154.

Wyss, J. M., & Sripanidkulchai, K. (1984). The topography of the mesencephalic and pontine projections from the cingulate cortex. *Brain Research, 293,* 1–15.

Yeckel, M. F., & Berger, T. W. (1989). Long-term potentiation of monosynaptic entorhinal cortical input to CA3 pyramidal neurons of the hippocampus. *Society for Neuroscience Abstracts, 15,* 402.

Appendix A

A Formal Description of the Model

The model described in this article is depicted in Figure 1. Figures 2 and 3 show a proposed mapping of the model onto hippocampal and cerebellar areas of the brain. Short-term memory variables (X_{i1}, X_{i2}, and Y) and long-term variables (V_i and Z_i) have been introduced in the text. The model used in the present article differs in some aspects from the models offered by Grossberg and Levine (1987) and Schmajuk and DiCarlo (1989).

The sensory representation of CS_i, X_{i1}, is defined by

$$d(X_{i1})/dt = -K_1X_{i1} + K_2(K_3 - X_{i1})I_{i1} - K_4X_{i1}J_{i1}, \quad \text{(A1)}$$

where $-K_1X_{i1}$ represents the passive decay of STM, K_2 represents the rate of increase of X_{i1}, constant K_3 is the maximum possible value of X_{i1}, I_{i1} is the total excitatory input, and J_{i1} represents the total inhibitory input. K_3 can be regarded as the number, or the percentage, of cells or membrane active sites that can be excited. Therefore, $(K_3 - X_{i1})$ represents the number, or the percentage, of inactive sites that can be excited, and X_{i1} the number of active sites that can be inhibited.

Grossberg and Levine (1987) assumed that positive feedback signals trigger a process of habituation that steadily attenuates the size of the feedback signals. For simplicity, the present article assumes no attenuation, and the total excitatory input, I_{i1}, is given by

$$I_{i1} = R_1(XCS_i) + K_5X_{i1}^m + K_6R_1(XCS_i)X_{i2}, \quad \text{(A2)}$$

where $R_1(XCS_i)$ represents the activity of a node excited by CS_i, and $K_5X_{i1}^m$ represents a positive feedback from X_{i1} to itself. $K_6R_1(XCS_i)X_{i2}$ represents a signal from X_{i2} to X_{i1} that is active only if CS_i is present. This last term, that can be regarded as a presynaptic modulation of X_{i2} by CS_i, avoids the activation of sensory representations by drive representations in the absence of CS_i.

We assume that CS_i activates node XCS_i according to

$$XCS_i = -K_7XCS_i + K_8(K_9 - XCS_i)CS_i. \quad \text{(A3)}$$

The output of the XCS_i node is a sigmoid given by

$$R_1(XCS_i) = XCS_i^n/\beta_1^n + XCS_i^n. \quad \text{(A4)}$$

As in Grossberg and Levine (1987), we assume that the total inhibitory input to X_{i1}, J_{i1}, is the sum of the activities of all other nodes, $\Sigma_{j\neq i}X_{j1}$. Therefore, J_{i1} is given by

$$J_{i1} = \Sigma_{j\neq i}R_2(X_{j1}), \quad \text{(A5)}$$

where $R_2(X_{j1})$ equals 0 if $X_{j1} < 0.2$, and $R_2(X_{j1}) = X_{j1}$ if $X_{j1} \geq 0.2$.

Activity in the drive representation node is given by

$$dY/dt = -K_{10}Y + K_{11}(\Sigma_iX_{i1}V_i + US), \quad \text{(A6)}$$

where $-K_{10}Y$ represents the passive decay of drive representation activity, $\Sigma X_{i1}V_i$ is the sum of sensory representations gated by the corresponding LTM traces, and US is the US input to the drive representation node. Notice that Grossberg and Levine (1987) assumed that the US acts on the sensory input, thereby explaining ISI effects, whereas we assume that the US acts only on the drive node and that the CS is delayed in XCS_i. We assume that Y is the output of the system and is proportional to the sum of the conditioned response (CR) and the unconditioned response (UR).

Grossberg and Levine (1987) assumed that the signal from Y activates the LTM of Z_i, whereas in the present article, we assume that the sensory representation X_{i1} activates LTM trace Z_i and determines the activity of X_{i2}. Therefore,

$$d(X_{i2})/dt = -K_{12}X_{12} + K_{13}X_{i1}^mZ_i. \quad \text{(A7)}$$

Although Grossberg and Levine (1987) assumed that associations of sensory representation X_{i1} with the drive representation, V_i, undergo extinction even when X_{i1} is zero, we assume that changes in V_i are possible only when X_{i1} is active. Also, contrasting with Grossberg and Levine, we assume that V_i has a maximum value. Changes in V_i are given by

$$d(V_i)/dt = -K_{14}V_iX_{i1} + K_{15}(K_{16} - V_i)YX_{i1}, \quad \text{(A8)}$$

where $-K_{14}V_iX_{i1}$ is the active decay in V_i when X_{i1} is active, and $K_{15}(K_{16} - V_i)YX_{i1}$ is the increment in V_i when Y and X_{i1} are active together. K_{16} can be regarded as the number, or percentage, of cells or membrane patches that can be modified by learning. Therefore, $(K_{16} - V_i)$ represents the number, or percentage, of unmodified sites that can increase the efficacy of their connection, and V_i represents the number of already-modified sites that can decrease their connectivity. Notice that Equation A8 is a Hebbian rule (V_i increases with concurrent pre- and postsynaptic activity) with extinction (V_i decreases with presynaptic activity alone).

As in Grossberg and Levine (1987), Equation A8 generates secondary reinforcement. This is so because, by Equation A6, Y is activated either by presentation of the US or of a CS already asso-

(*Appendixes continue on next page*)

ciated with the US. Therefore, if CS_1 is associated with the US, it generates activity Y, which becomes associated with X_{21} by Equation A8.

For simplicity, Grossberg and Levine (1987) assumed that Z_i was identical to V_i. To explain the savings effect seen in the acquisition–extinction series, we conjectured that Z_i varies at a slower rate than V_i. Therefore, we have computed Z_i with

$$d(Z_i)/dt = -K_{17}Z_iX_{i1}^m + K_{18}(K_{19} - Z_i)YX_{i1}^m, \quad \text{(A9)}$$

where $-K_{17}Z_iX_{i1}^m$ is the active decay in Z_i when X_{i1}^m is active, and $K_{18}(K_{19} - Z_i)YX_{i1}^m$ is the increment in Z_i when Y and X_{i2} are active together. Assuming that X_{i1} represents presynaptic activity and that Y characterizes postsynaptic excitation, Equation A9 states that synapse Z_i is potentiated with concurrent presynaptic and postsynaptic activities ($X_{i1} > 0$ and $Y > 0$) and depotentiated when the presynaptic neuron is active ($X_{i1} > 0$) but the postsynaptic neuron is inactive ($Y = 0$). Consequently, Equation A9 is in agreement with Kelso et al.'s (1986) and Stanton and Sejnowski's (1989) data showing that LTP increases when the presynaptic membrane is active in the presence of postsynaptic depolarization and with Stanton and Sejnowski's data showing that LTP decreases when the presynaptic membrane is active in the absence of postsynaptic depolarization.

The output of the system (i.e., the CR and UR) is another sigmoid given by

$$R3(Y) = Y^2/(Y^2 + \beta_2^2). \quad \text{(A10)}$$

Appendix B

A Formal Description of the STM Regulation Hypothesis

HL Effects

After HL, sensory representation X_{i1} is given by

$$d(X_{i1})/dt = -K_1X_{i1} + K_2(K_3 - X_{i1})I_{i1}. \quad \text{(B1)}$$

After HL, the total excitatory input, I_{i1}, is given by

$$I_{i1} = R_1(XCS_i). \quad \text{(B2)}$$

After HL, activity in the drive representation node remains unchanged and is given by

$$dY/dt = -K_{10}Y + K_{11}(\Sigma_iX_{i1}V_i + US). \quad \text{(B3)}$$

After HL, changes in V_i are still given by

$$d(V_i)/dt = -K_{14}V_iX_{i1} + K_{15}(K_{16} - V_i)YX_{i1}. \quad \text{(B4)}$$

After HL, incentive motivation values Z_i are zero.

LTP Effects

After LTP, incentive motivation associations Z_i are assigned an initial value five times greater than its normal initial value.

LTP Blockade Effects

After LTP blockade, it is assumed that changes in incentive motivation associations are given by

$$d(Z_i)/dt = 0. \quad \text{(B5)}$$

Appendix C

Simulation Parameters

Although the model is a real-time model, computer simulations of the model generate values of the relevant variables at discrete time instants. In our simulations we assume that one computer time step is equivalent to 10 ms. Each trial consisted of 500 steps, equivalent to 5 s. Unless specified, the simulations assumed 200 ms CSs, the last 50 ms of which overlaps the US. CS onset was at 200 ms. Parameters were selected so that simulated asymptotic values of V_i were reached in around 10 acquisition trials. Because asymptotic conditioned NM responding is reached in approximately 200 real trials (Gormezano, Kehoe, & Marshall, 1983), one simulated trial is approximately equivalent to 20 experimental trials.

Parameter values are $K_1 = 0.05$, $K_2 = 0.095$, $K_3 = 1.5$, $K_4 = 3$, $K_5 = 0.6$, $K_6 = 10$, $K_7 = 0.07$, $K_8 = 0.18$, $K_9 = 1$, $K_{10} = 1$, $K_{11} = 0.34$, $K_{12} = 1$, $K_{13} = 1$, $K_{14} = 0.0155$, $K_{15} = 0.04$, $K_{16} = 1$, $K_{17} = 0.0002$, $K_{18} = 0.001$, $K_{19} = 1.5$, $\beta_1 = 0.62$, $\beta_2 = 0.03$, $n = 70$, $m = 1.5$. The initial value of V_i was 0. The initial value of Z_i was 0.1. These values were kept constant for all simulations for the normal and HL cases. The effect of LTP induction and kindling were simulated by assigning to all Z_is an initial value equal to 0.5. The effects of LTP blockade were simulated by making K_{17} and K_{18}, and therefore all changes in Z_is, equal to zero.

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