NEED RECURRENT GATED DIPOLE TO EXPLAIN SECONDARY INHIBITORY CONDITIONING

1. Pair
   Onset of CS₁ with shock

   CS₁ → Fear

2. Pair
   Onset of CS₂ with offset of CS₁

   CS₁ ON
   OFF
   GATE
   CS₂

READ (I) CIRCUIT
Grossberg & Schmajuk (1987)

REcurrent Associative Diople
### CONDITIONING PARADIGMS

**Primary Excitatory**
- CS1
- US

**Primary Inhibitory**
- CS1
- US

**Secondary Excitatory**
- CS2
- US

**Secondary Inhibitory**
- CS2
- CS1
- US

**Partial**
- CS1
- US

### PRIMARY EXCITATORY CONDITIONING

**Aquisition**
- CS
- US

**Extinction**
- CS
- NO US

**US**
- CS Read-out
- ON
- OFF
- LTM (ON)

No passive forgetting
PRIMARY INHIBITORY CONDITIONING
CS becomes a "conditioned inhibitor"

Aquisition
CS
US

Extinction
CS
NO US

US → REBOUND
ON
OFF
LTM (ON)

SECONDARY EXCITATORY CONDITIONING

CS₁ - US
CS₂ - CS₁

LTM (ON-Primary)
LTM (ON-Secondary)
SECONDARY INHIBITORY CONDITIONING

CS\textsubscript{1} - US
CS\textsubscript{2} - CS\textsubscript{1} OFF

LTM (ON-Primary)

LTM (OFF-Secondary)

READ I EQUATIONS

Accepted + US + Feedback On-Activation
\[
\frac{dx}{dt} = -ax + f(u) + f(u_0)
\]

Accepted + Feedback Off-Activation
\[
\frac{dx}{dt} = -ax + f(u)
\]

Un Transmitter
\[
\frac{dy}{dt} = y(1 - y) - Cy(z)z
\]

OFF/Transmitter
\[
\frac{dy}{dt} = y(1 - y) - C(p(z)z
\]

Gated On-Activation
\[
\frac{dx}{dt} = -ax + b_1 q_1 x_1
\]

Gated Off-Activation
\[
\frac{dx}{dt} = -ax + b_0 q_0 x_2
\]

Normalized Opponent On-Activation
\[
\frac{dx}{dt} = -ax + b_1 q_1 x_1
\]

Normalized Opponent Off-Activation
\[
\frac{dx}{dt} = -ax + b_0 q_0 x_2
\]

Objective by CS Inputs
\[
\frac{dz}{dt} = -az + bx + b_i y_1 + c_1 x_2
\]

Un-Conditioned Reinforcer Learning
\[
\frac{dz}{dt} = x(z) + bx + b_i y_1 + c_1 x_2
\]

Un Output Signal
\[
G_u = [u]
\]

Off Output Signal
\[
G_o = [0]
\]
ASSOCIATIVE LEARNING
FORGETTING
e.g., Remember childhood experiences
Forgetting is NOT PASSIVE
Forgetting is SELECTIVE

SELECTIVE: Larger memory capacity
PROBLEM: Why doesn't memory SATURATE?

SELECTIVE FORGETTING
Not "just" gated memory decay
GATED STEEPEST DESCENT

\[
\frac{d}{dt} z_{ij} = \epsilon(x_i) \left[ -z_{ij} + g(x_j) \right]
\]

\[
> 0 \quad \approx 0
\]

\[
\frac{d}{dt} z_{ij} = \epsilon(x_j) \left[ -z_{ij} + f(x_i) \right]
\]

NECESSARY, BUT NOT SUFFICIENT
EXPERIMENTAL SUPPORT

Levy et al., 1983+
Singer et al., 1979+

Hebbian
Anti-Hebbian …

An early NN prediction

DISCONFIRMED EXPECTATIONS LEAD TO SELECTIVE FORGETTING
**PAVLOVIAN CONDITIONING**

Forgetting = Extinction

CS = Conditioned Stimulus
   (Bell, Light,...)

US = Unconditioned Stimulus
   (Shock, Food, …)

**MAIN FACT ABOUT FORGETTING**

A conditioned excitor extinguishes

A conditioned inhibitor does not extinguish

DeVito, 1980  
Owren and Kaplan, 1981  
Witcher, 1978  
Zimmer-hart and Rescorla, 1974

**NOT YET EXPLAINED BY OTHER MODELS**

**CONDITIONED EXCITOR EXTINGUISHES**

<table>
<thead>
<tr>
<th>LEARNING PHASE</th>
<th>FORGETTING PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS₁ (BELL) → US</td>
<td>CS₁ (BELL) → FORGETTING</td>
</tr>
<tr>
<td>CS₁ → FEAR(-)</td>
<td></td>
</tr>
</tbody>
</table>

LET US = SHOCK
### CONDITIONED INHIBITOR DOES NOT EXTINGUISH

<table>
<thead>
<tr>
<th>LEARNING PHASE</th>
<th>FORGETTING PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(LIGHT)</td>
<td></td>
</tr>
<tr>
<td>1) CS₁ → SHOCK</td>
<td>CS₂ → NO FORGETTING</td>
</tr>
<tr>
<td>CS₁ → FEAR (⁻)</td>
<td></td>
</tr>
</tbody>
</table>

**CS₂ is relevant; it predicts US change**

SAME CS could be used! SAME "teacher" in forgetting phase! Something else must be going on, or else CAUSALITY would be violated!

### CONDITIONED EXCITOR EXTINGUISHES

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<td>CS₁ → US</td>
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</tr>
<tr>
<td>CS₁ → FEAR(⁻)</td>
<td></td>
</tr>
<tr>
<td>CS₁ → SHOCK</td>
<td></td>
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</tbody>
</table>

CS₁ is conditioned to an expectation of shock

THE EXPECTATION OF SHOCK IS DISCONFIRMED

SG © 2005
### CONDITIONED INHIBITOR DOES NOT EXTINGUISH

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<thead>
<tr>
<th>LEARNING PHASE</th>
<th>FORGETTING PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1)</strong> (LIGHT)</td>
<td></td>
</tr>
<tr>
<td>$CS_1$ → SHOCK</td>
<td></td>
</tr>
<tr>
<td>$CS_1$ → FEAR (-)</td>
<td></td>
</tr>
<tr>
<td><strong>2)</strong> $CS_1 + CS_2$ (BELL)</td>
<td></td>
</tr>
<tr>
<td>$CS_2$ → RELIEF (+)</td>
<td></td>
</tr>
<tr>
<td>$CS_2$ → NO SHOCK</td>
<td></td>
</tr>
<tr>
<td>$CS_2$ (BELL) → NO FORGETTING</td>
<td></td>
</tr>
</tbody>
</table>

**THE EXPECTATION THAT “NO SHOCK” FOLLOWS $CS_2$ IS NOT DISCONFIRMED!**

### CONCLUSIONS

1. No passive forgetting (inhibitor)

2. Nonoccurrence of EXPECTED shock causes active forgetting (excitor)

---

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At the moment of unexpected disconfirmation the correct answer is unknown to the system

NOVELTY

PARALLEL LEARNING PROCESSES
NO ONE "ENGRAM"

Learn sensory expectations (1)
Learn conditioned reinforcer (2)

CS

Sensory representation of US
Emotional representation of US

Disconfirmation of (1) → forgetting of (2)

(1) recognition learning

(2) reinforcement learning
**WHAT ARE THE MECHANISMS?**

**I. ANTAGONISTIC REBOUND**
**DISCONFIRMED EXPECTATION**

<table>
<thead>
<tr>
<th>Nonoccurrence of expected punishment</th>
<th>(-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>relief (relaxation)</td>
<td>(+)</td>
</tr>
<tr>
<td>Nonoccurrence of expected reward</td>
<td>(+)</td>
</tr>
<tr>
<td>frustration</td>
<td>(-)</td>
</tr>
</tbody>
</table>

**SUDDEN REDUCTION OF REINFORCING EVENT**

| Sudden reduction of punishment        | (-)  |
| relief                                | (+)  |
| Sudden reduction of reward            | (+)  |
| frustration                           | (-)  |

**II. OPPONENT EXTINCTION**

Grossberg (1975)
Grossberg and Schmajuk (1987)

Selective forgetting = opponent extinction

No passive forgetting
No associative saturation
Disconfirmed expectation → active forgetting
A CS CAN BE CONDITIONED TO BOTH THE ON AND OFF CHANNELS OF A GATED DIPOLE

LEARN ON-RESPONSE

Disconfirmed expectation → antagonistic rebound
OFF-channel is conditioned

Zero net output

What about ASSOCIATIVE SATURATION?
LEARN NET DIPOLE OUTPUT PATTERN

Opponent "decision" controls learning
Cf., competitive learning

DISSOCIATION OF LTM READ-OUT AND READ-IN

Opponent Competition

Old Predictions
Ca++ currents in learning (1968)
Role of dendritic spines in learning (1975)
Cf., recent work of Hasselmo
LEARNING AND MISMATCH OF SENSORY EXPECTATION

Adaptive Resonance Theory

Forgetting controlled by
2 interacting ART systems

(1) Recognition learning (1976)
(2) Recognition-reinforcement learning (1975)

Sensory mismatch in (1)  →
Nonspecific arousal burst  →
Antagonistic rebound in (2)  →
Opponent extinction (forgetting)
SAME EXPLANATION FOR UNBLOCKING!

Conditioned Inhibitor:

CS₁ + CS₂ → No shock

Unblocking:

CS₁ + CS₂ → US₂ (≠US₁)

CS₂

{ Relief
   if US₂ < US₁
   Fear
   if US₂ > US₁

Also need: Unexpected event (CS₂) is stored more actively in STM due to STM reset by expectancy mismatch

FOCUS ON HOW ADAPTIVE TIMING INTERACTS WITH RECOGNITION, REINFORCEMENT, & ACTION

Role of

Hippocampal formation

(dendrate granule cells, CA3 pyramid cells, NMDA receptors)

Outline

Behavioral problems
Computational principles
Local neural circuits
Global neural architecture
CONNECTION WITH RECOGNITION LEARNING
ADAPTIVE RESONANCE THEORY
(Carpenter & Grossberg, 1987)