Attention for learning:
The striatal cholinergic system in reward-based learning

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Real world learning
Reward-based learning in the brain

- Reinforcement learning in the striatum

Attention in the striatum?

- Cholinergic interneurons
- Cholinergic gating of RL in the striatum

Attention for learning

- Cholinergic-gated RL with multiple stimuli
Reinforcement learning

Houk, Adams & Barto 1995
Suri & Schultz 1998
Joel et al., 2002
Reinforcement learning

cortex

striatum

substantia nigra
Reinforcement learning

Value

- cortex
- striatum
- substantia nigra
Reinforcement learning

cortex → striatum → substantia nigra

Prediction error
Reinforcement learning

\[ \delta(t) = R(t) + \gamma V(t) - V(t - 1) \]
Reinforcement learning

Dopamine-mediated plasticity

substantia nigra
Classical conditioning

Trial 1

MSN firing rate

DA firing rate

Time (s)

0 1 2 3 4

baseline

Time (s)

0 1 2 3 4

baseline
Classical conditioning

Trial 2

**MSN firing rate**

**DA firing rate**

Time (s)

baseline

Time (s)
Classical conditioning

Trial 4

MSN firing rate
baseline

DA firing rate
baseline
Classical conditioning

Trial 20

MSN firing rate

DA firing rate

Time (s)
Classical conditioning

Cortico-striatal weight

MSN value

Trial

Synaptic weight vs. Trial

Max firing rate vs. Trial
Outline

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CINs learn to pause

Cholinergic interneurons

Aosaki et al.
*Journal of Neuroscience*, 1994

Morris et al., 2004
Apicella, 2002
CI-gated RL in the striatum

Schulz & Reynolds, 2013
Bradfield et al., 2013
CIN pause only to relevant events

CM-Pf neurons

Cholinergic interneurons

Matsumoto et al.

_J Neurophysiol_, 2001
Cholinergic interneurons

- thalamus
- spiny neurons
- cortex

Calabresi et al., 2000
Cragg, 2006
Cholinergic interneurons

Suzuki et al., 2001
A functional role for cholinergic signalling?

Cholinergic pause reduces synaptic inhibition at the cortico-striatal synapses.

Cholinergic pauses as a stimulus-locked window during which cortico-striatal learning is amplified.
CI-gated RL in the striatum

- **MSN firing rate**
  - Baseline

- **CIN firing rate**
  - Baseline

- **DA firing rate**
  - Baseline
CI-gated RL in the striatum

- **MSN firing rate**
- **CIN firing rate**
- **DA firing rate**
CI-gated RL in the striatum

- **MSN firing rate**
  - Baseline

- **CIN firing rate**
  - Baseline

- **DA firing rate**
  - Baseline
CI-gated RL in the striatum

MSN firing rate

CIN firing rate

DA firing rate

Time (s)
CI-gated RL in the striatum

MSN value

CIN gating

![Graph showing the relationship between Firing rate at stimulus and Trial for MSN value and CIN gating.](image-url)
Cholinergic pauses persist for long periods after a stimulus-reward association is learnt.

Cholinergic pauses reflect a history of the reward-relevance of a given stimulus.
Extinction

MSN firing rate

CIN firing rate

DA firing rate
Extinction

- **MSN firing rate**
  - Baseline

- **CIN firing rate**
  - Baseline

- **DA firing rate**
  - Baseline

Time (s)
Extinction

MSN firing rate

CIN firing rate

DA firing rate
Extinction

MSN firing rate

CIN firing rate

DA firing rate

Time (s)
0 1 2 3 4

baseline

baseline

baseline

Time (s)
0 1 2 3 4

5
10
Extinction

MSN value

CIN gating
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Multi-stimulus learning

Initial exposure

Tone

Light
Multi-stimulus learning

Initial exposure

Tone

Light

Extinction
Multi-stimulus learning

Test phase

Tone (relevant)

Light (irrelevant)

Clicks (novel)
Multi-stimulus learning

MSN value

Firing rate at stimulus

CIN gating

Firing rate at stimulus

relevant (tone)
irrelevant (light)
 novel (clicks)
Multi-stimulus learning

Increased learning rate for stimuli previously relevant for reward

**MSN value**

**CIN gating**

relevant (tone)
irrelevant (light)
novel (clicks)
Multi-stimulus learning

Delayed learning for previously irrelevant stimuli

**MSN value**

**CIN gating**

relevant (tone)
irrelevant (light)
novel (clicks)
Summary

• Cholinergic interneurons in the striatum learn to pause at motivationally relevant events
• Cholinergic interneurons in the striatum learn to pause at motivationally relevant events

• Pauses in cholinergic activity may act as attentional windows during which learning is amplified
• Cholinergic interneurons in the striatum learn to pause at motivationally relevant events

• Pauses in cholinergic activity may act as attentional windows during which learning is amplified

• This mechanism may act in multi-stimulus environments to gate learning according to the relevance of a stimulus for reward
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