



Reward Based Decision Making

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Sloan-Swartz Meeting 2004, CSHL



Outline

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Adaptive Decision Making

Spiking Network Model

Reward Gated Plasticity

Simulation Results

Conclusion

■ Adaptive decision making and matching task



Outline

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- Adaptive decision making and matching task
- Spiking network model for decision making



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- Adaptive decision making and matching task
- Spiking network model for decision making
- Reward gated plasticity



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- Adaptive decision making and matching task
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- Reward gated plasticity
- Simulation results



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Adaptive Decision Making

- Real World
- Matching Law
- Remarks and Motive
- Matching Task in Monkeys
- Matching Behavior

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Adaptive Decision Making



Real World

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There are many situations where the mapping between an action and its outcome is not fixed.



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There are many situations where the mapping between an action and its outcome is not fixed.

- Social and economic interactions



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There are many situations where the mapping between an action and its outcome is not fixed.

- Social and economic interactions

- Foraging behavior in natural environment



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There are many situations where the mapping between an action and its outcome is not fixed.

Foraging behavior



Matching Law

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The animal allocates its time between competing *choices* in a manner that it matches the relative *return* from those choices.

$$\frac{C_i}{C_1 + C_2 + \dots + C_n} = \frac{R_i}{R_1 + R_2 + \dots + R_n}$$

$$\text{return} = (\text{reward magnitude}) \times (\text{rate})$$

Herrnstein R.J., "The Matching Law, Papers in Psychology and Economics"



Remarks and Motive

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■ Why do they match?



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- Why do they match?
- What is the local choice rule?



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- Why do they match?
- What is the local choice rule?
- What is the neural basis of the matching behavior?



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What is the neural basis of the matching behavior?



Matching Task in Monkeys

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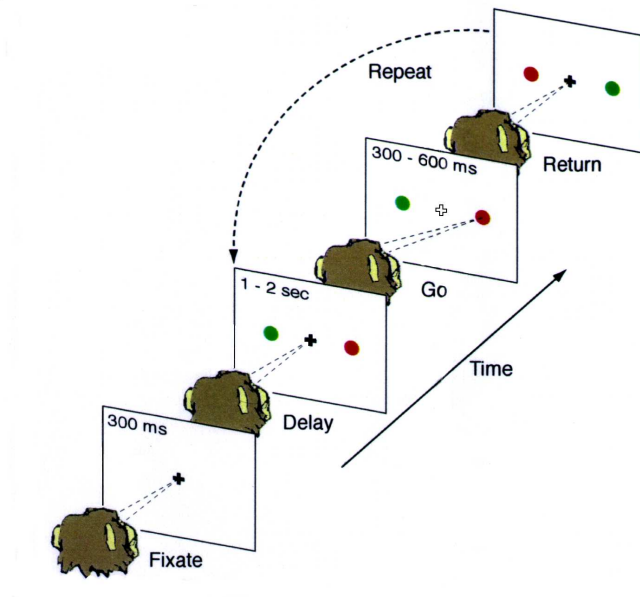
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Sugrue L.P., Corrado G.S., Newsome W.T., Science 2004



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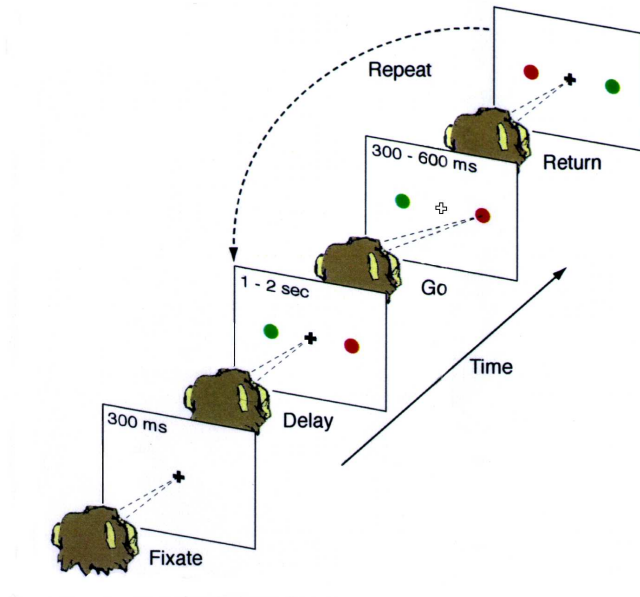
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■ reward assignment is stochastic

Sugrue L.P., Corrado G.S., Newsome W.T., Science 2004



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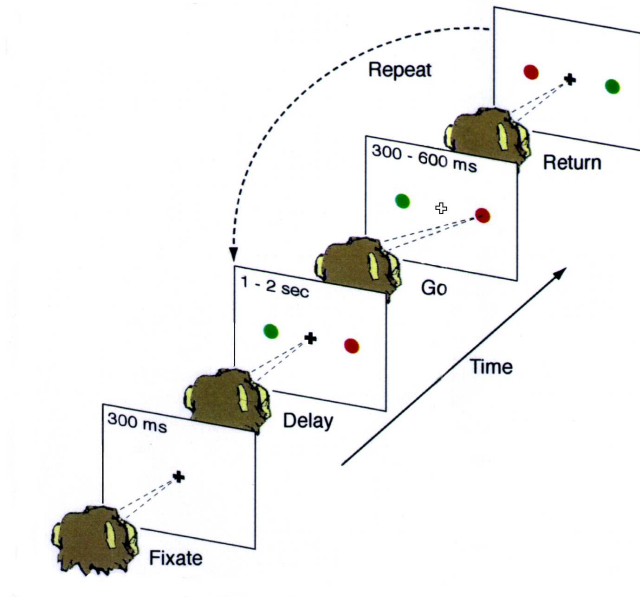
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- reward assignment is stochastic
- reward is persistent

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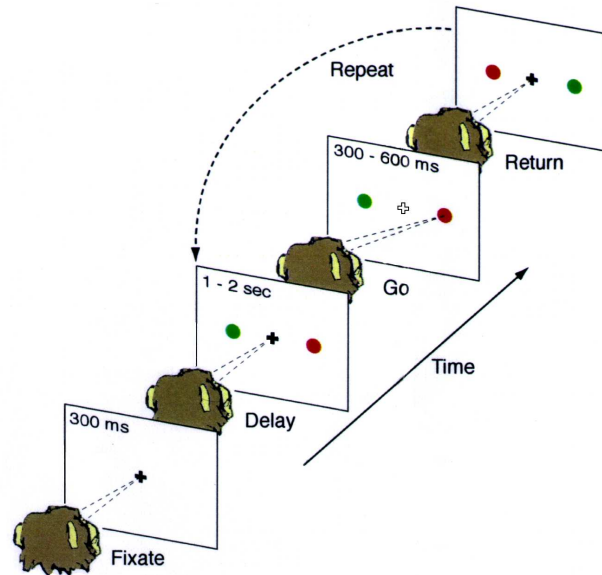
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- reward assignment is stochastic
- reward is persistent
- changeover delay

Sugrue L.P., Corrado G.S., Newsome W.T., Science 2004



Matching Behavior

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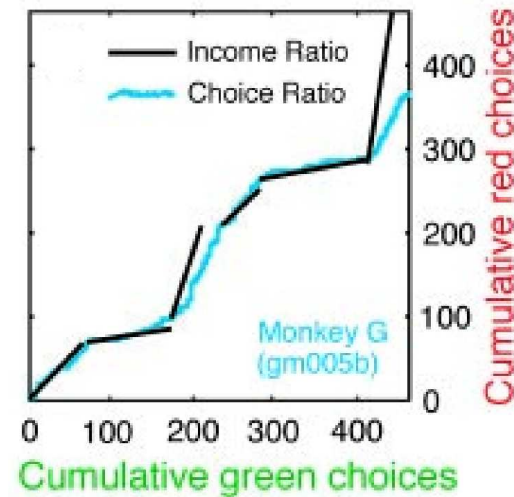
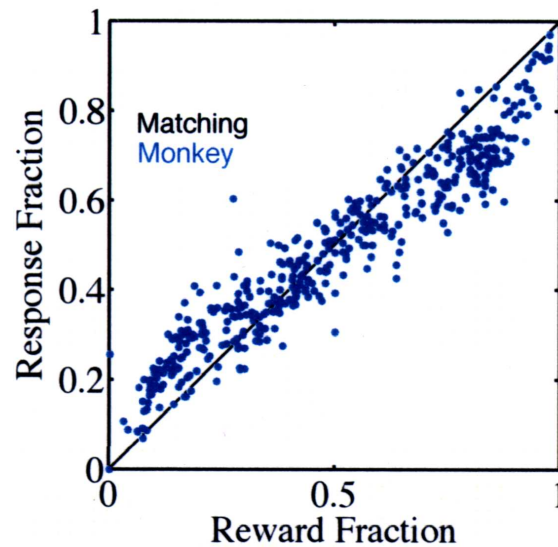
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Monkeys show approximate matching.



Sugrue L.P., Corrado G.S., Newsome W.T., Science 2004



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Network Behavior

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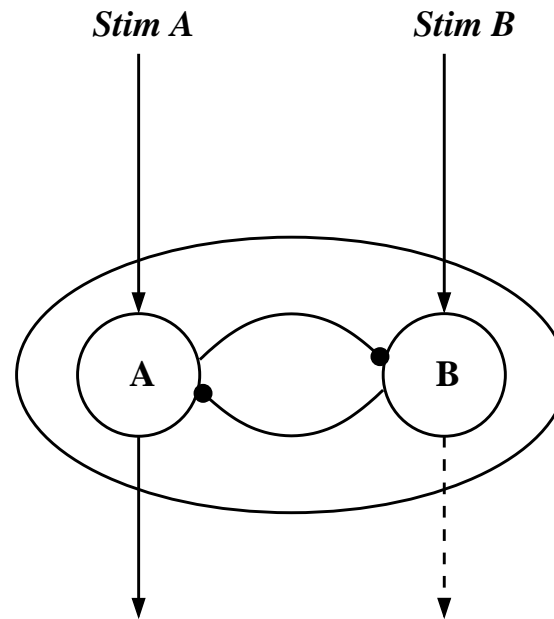
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A decision-making network with winner-takes-all property.





Network Behavior

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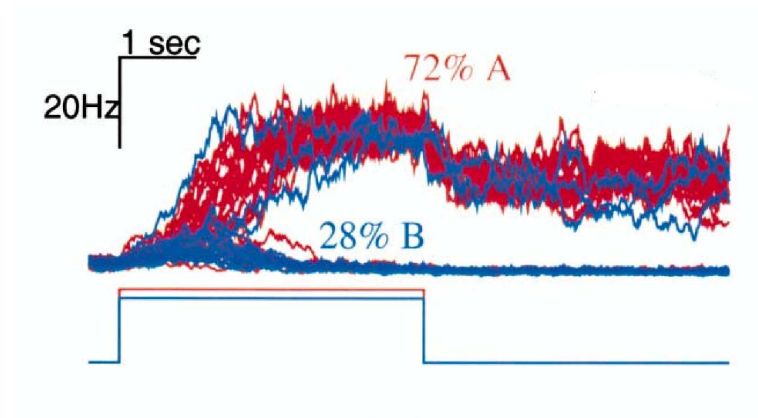
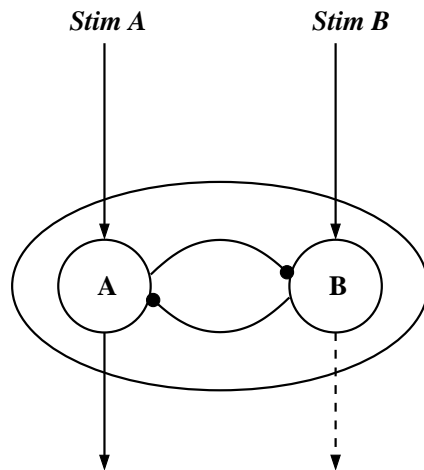
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The network choice is determined by:

1. Strength of the inputs
2. Intrinsic noise in the neurons spiking



Wang X.J., Neuron 2002



Stochastic Response

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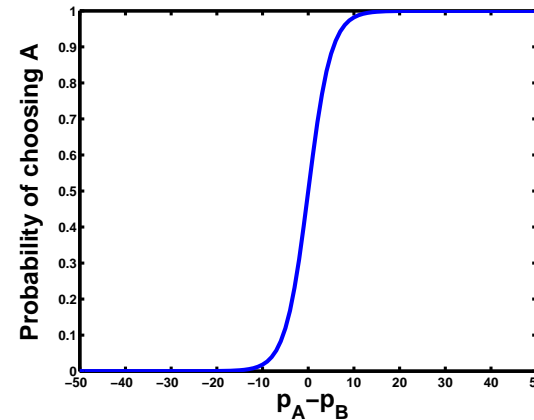
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The stochastic network behavior as a function of synaptic strengths is approximately sigmoidal.

$$\Pi = \frac{1}{1 + \exp\left(-\frac{p_A - p_B}{\sigma}\right)}$$



p_A : Probability of afferent synapses to population A being in potentiated state.

σ : Sensitivity of the network to the biased inputs



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- Three-factor Rule
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Reward Gated Plasticity



Three-factor Rule

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- Three-factor Rule

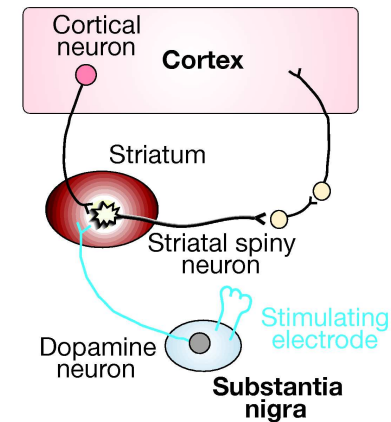
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- Conclusion

Three factors for dopamine-dependent plasticity:
presynaptic activity, postsynaptic activity, dopamine (reward signal).



Reynolds J.N., Hyland B.I., Wickens J.R., Nature 2001

Reynolds J.N., Wickens J.R., Neural Network 2002



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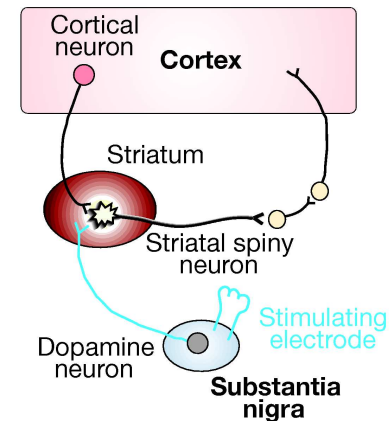
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■ $(pre \uparrow post \uparrow) + \text{Dopamine} \rightarrow \text{LTP}$



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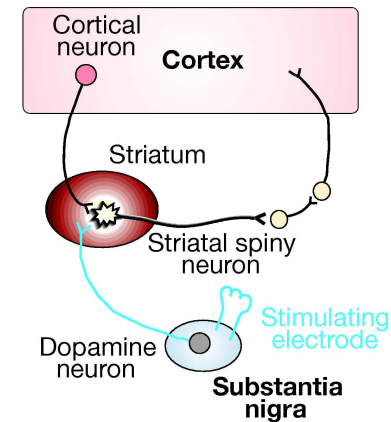
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- $(pre \uparrow post \uparrow) + \text{No Dopamine} \rightarrow \text{LTD}$



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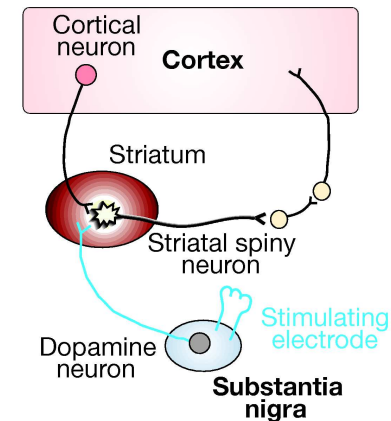
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- $(pre \uparrow post \uparrow) + \text{No Dopamine} \rightarrow \text{LTD}$
- $(pre \uparrow post \downarrow) + \text{Dopamine} \rightarrow \text{LTD/LTP}$



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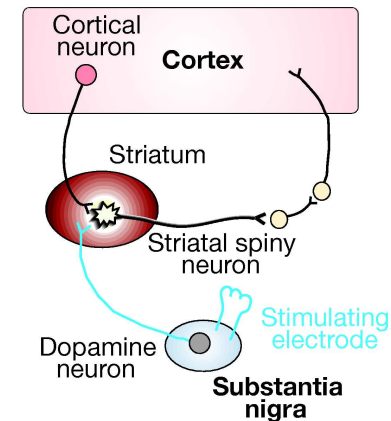
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- $(pre \uparrow post \uparrow) + \text{Dopamine} \rightarrow \text{LTP}$
- $(pre \uparrow post \uparrow) + \text{No Dopamine} \rightarrow \text{LTD}$
- $(pre \uparrow post \downarrow) + \text{Dopamine} \rightarrow \text{LTD/LTP}$
- $(pre \uparrow post \downarrow) + \text{No Dopamine} \rightarrow \text{No change}$



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Learning Rule

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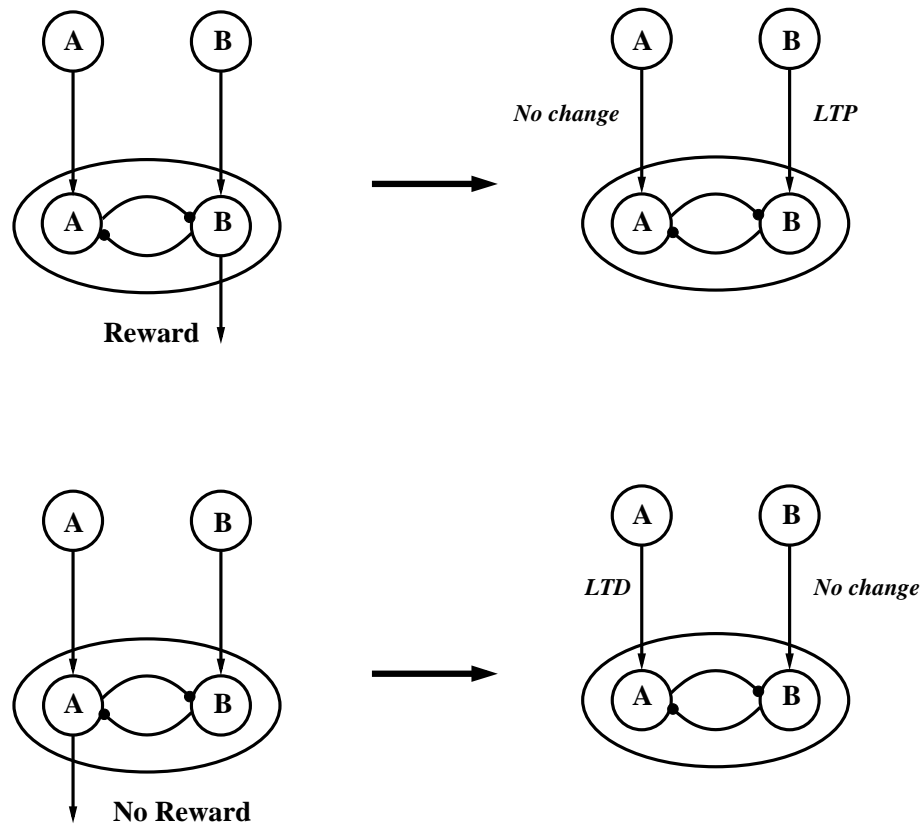
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Assumptions:

Presynaptic side is always active.

Postsynaptic side is active only for the winner population.





Stochastic Learning

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If the condition for learning is met, only a fraction of synapses are changed.

Amit D.J., Fusi S., Neural Comp. 1994

Fusi S., Biol. Cybernetic 2002



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■ Potentiation: $\Delta p_A = (1 - p_A)q_+$

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If the condition for learning is met, only a fraction of synapses are changed.

- Potentiation: $\Delta p_A = (1 - p_A)q_+$

- Depression: $\Delta p_A = -p_Aq_-$

Amit D.J., Fusi S., Neural Comp. 1994

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Global Behavior

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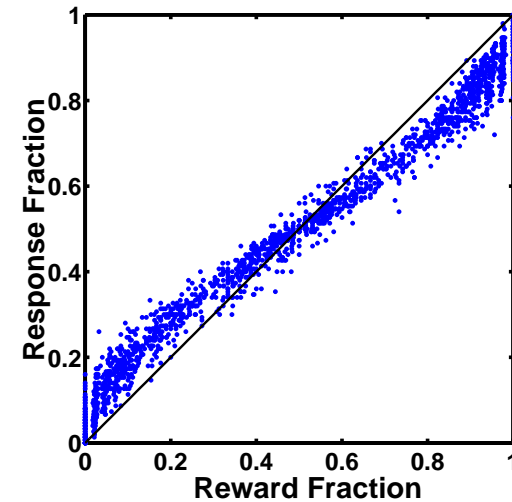
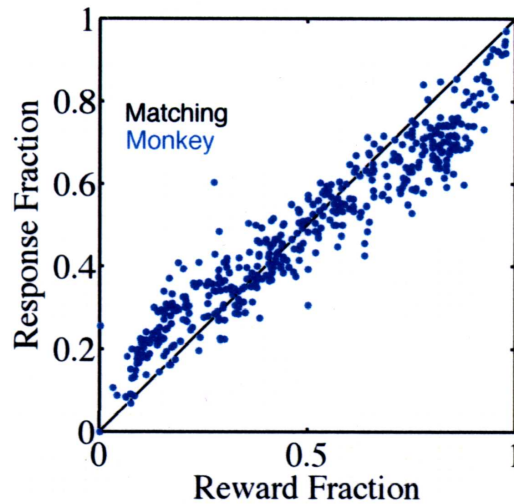
● Reward Tracking

● Choice-Triggered Averages

● Robustness

Conclusion

Model mimics the monkey's matching behavior.



Sugrue L.P., Corrado G.S., Newsome W.T., Science 2004



Local Behavior

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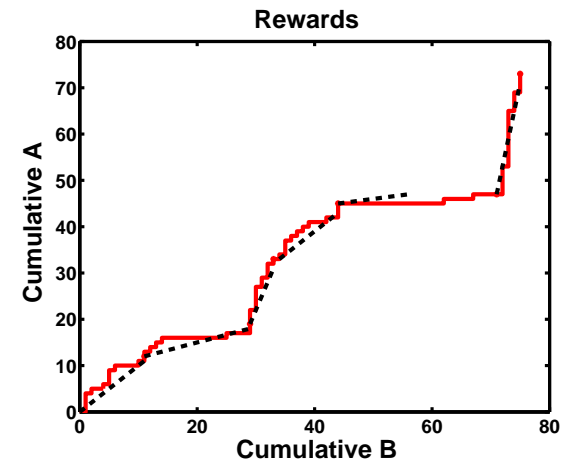
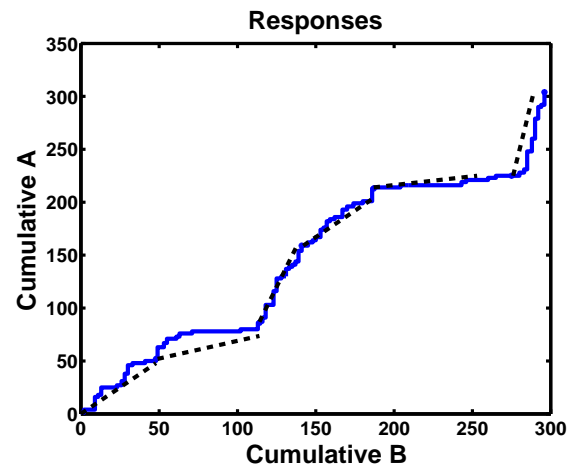
- Reward Tracking

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Conclusion

Model is able to track changes in the reward schedule.





Reward Tracking

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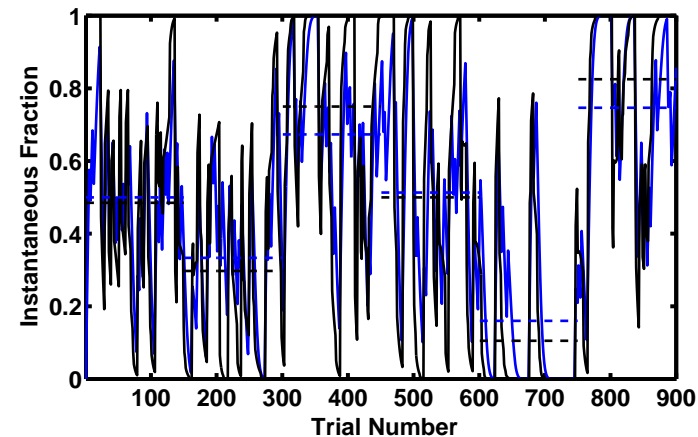
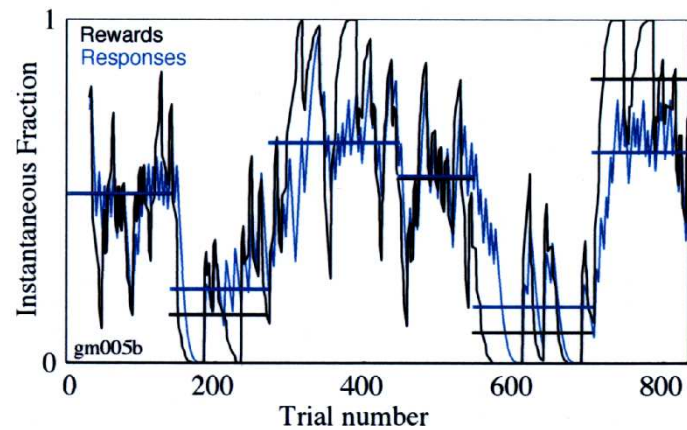
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Model tracks random changes in the reward delivery.





Choice-Triggered Averages

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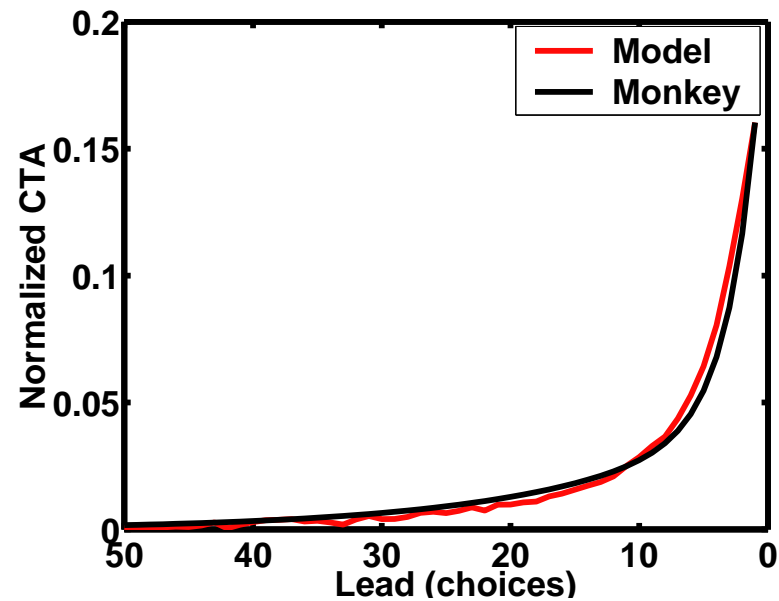
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Model is able to replicate the CTA curve.



Sugrue L.P., Corrado G.S., Newsome W.T., Science 2004



Robustness

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Model shows matching behavior and high reward harvesting rate for a wide range of parameters.



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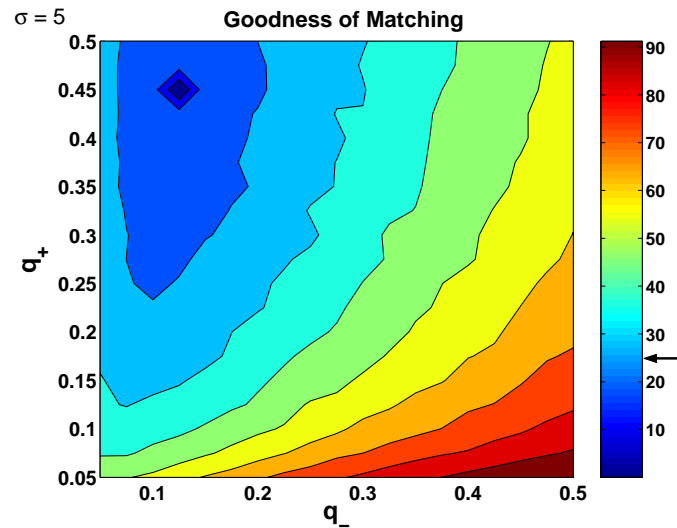
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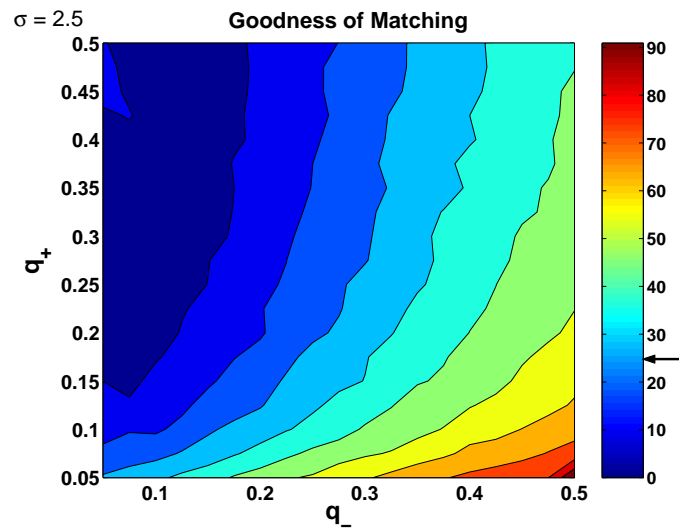
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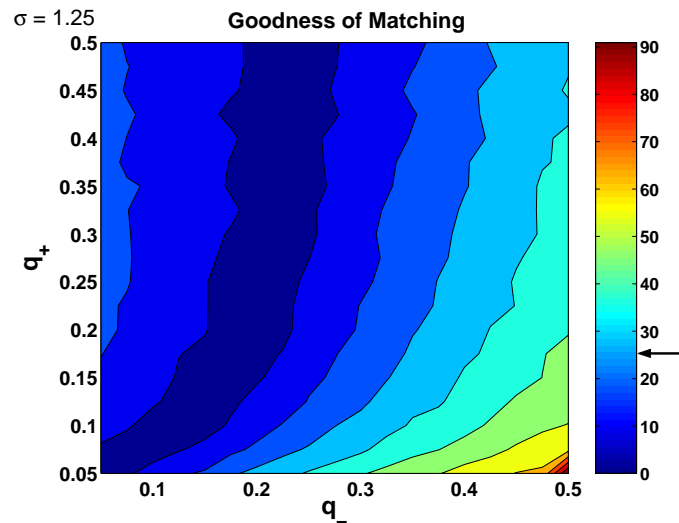
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Model shows matching behavior and high reward harvesting rate for a wide range of parameters.

Model is able to perform the matching task for different overall reward rates.



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- An adaptive decision-making network can be modeled using the main characteristics of working memory circuits.



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- An adaptive decision-making network can be modeled using the main characteristics of working memory circuits.
- Our model is able to replicate all of the behavioral data.



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- Functional form of choice dependence on reward history can be captured using particular values of parameters.



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- The simplest form of learning rule is very robust against changes in the network and environment.



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- The simplest form of learning rule is very robust against changes in the network and environment.
- Prediction ...



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- **Acknowledgment**

Stefano Fusi
Leo Sugrue
Wanglab members



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- Network Architecture
- Full Network
- Introducing Changeover Delay
- Optimal Solution in General
- Neuronal Recordings
- Robustness
- Type 1



Network Architecture

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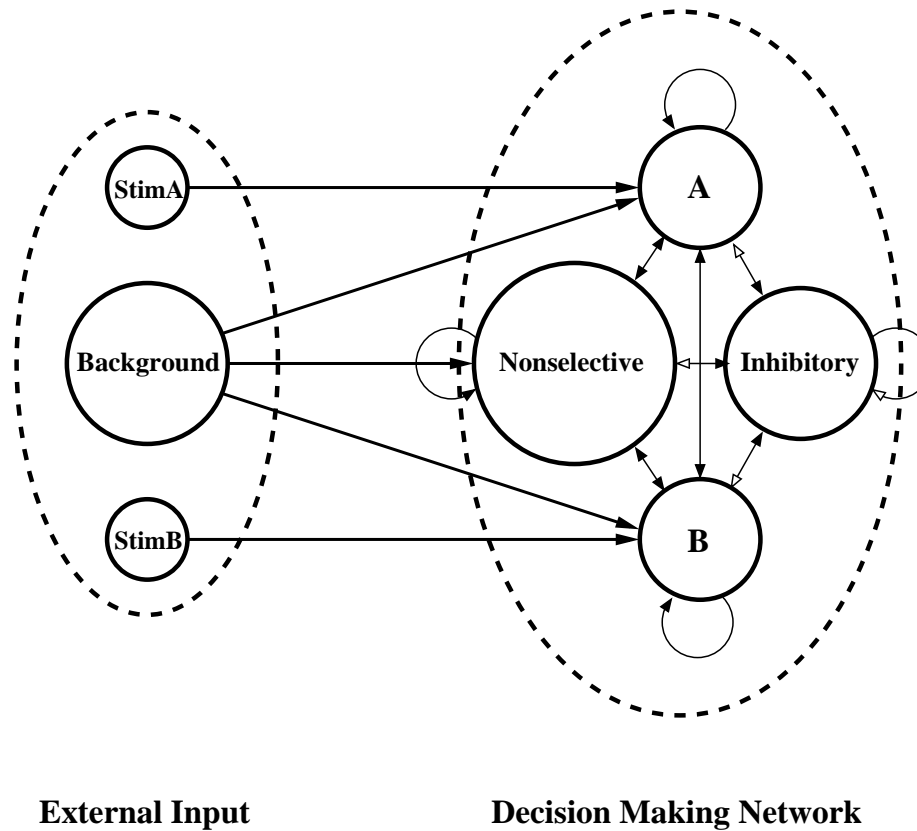
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Decision-making network with winner-take-all property.



Wang X.J., *Neuron* 2002



Full Network

A model which is able to perform remapping.

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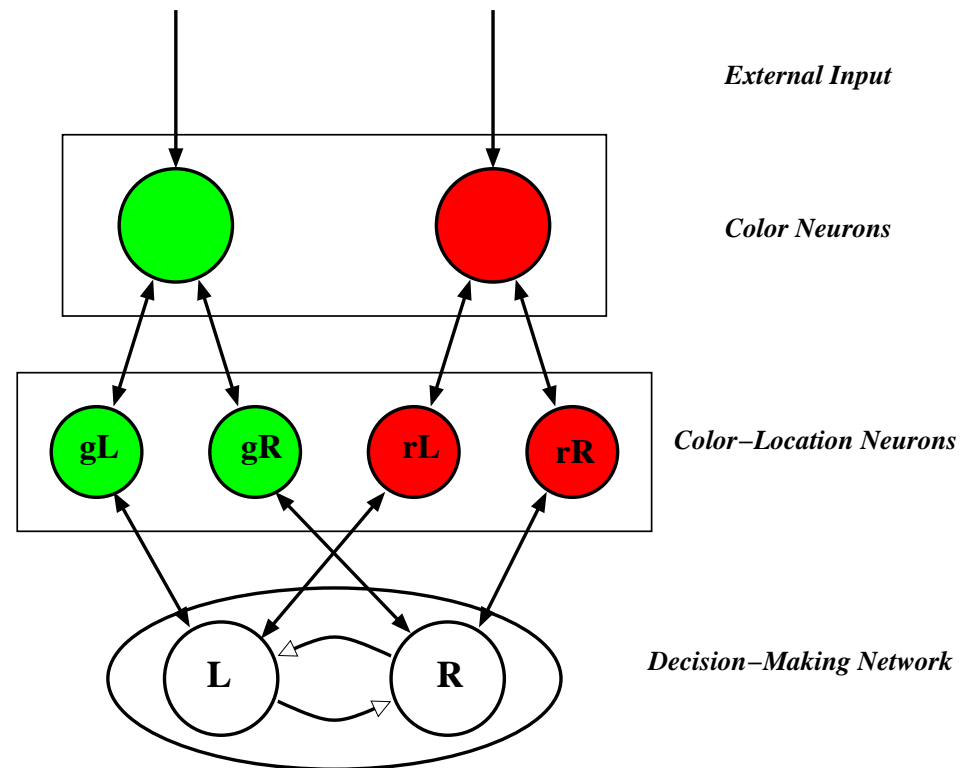
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Introducing Changeover Delay

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Spiking Network Model

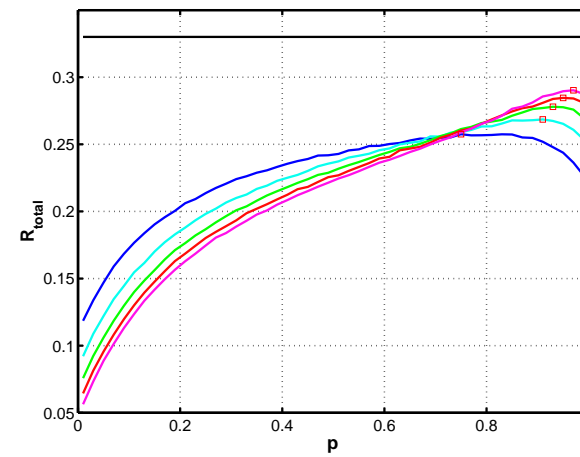
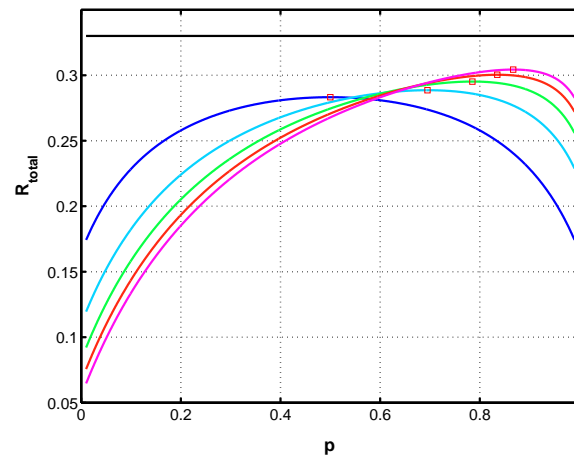
Reward Gated Plasticity

Simulation Results

Conclusion

- Network Architecture
- Full Network
- **Introducing Changeover Delay**
- Optimal Solution in General
- Neuronal Recordings
- Robustness
- Type 1

Introducing changeover delay, results in steeper total reward harvesting rate.





Optimal Solution in General

- Outline

Adaptive Decision Making

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In any matching task where the reward assignment on targets are independent of each other, a form of matching is an optimal solution.



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$$\frac{\partial R_1}{\partial p_1} = \frac{\partial R_2}{\partial p_2}$$



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$$\frac{\partial R_1}{\partial p_1} = \frac{\partial R_2}{\partial p_2}$$

$$\frac{p_{opt}}{1 - p_{opt}} = \sqrt{\frac{T'_1}{T'_2}} \times \frac{R_1}{R_2}$$



Neuronal Recordings

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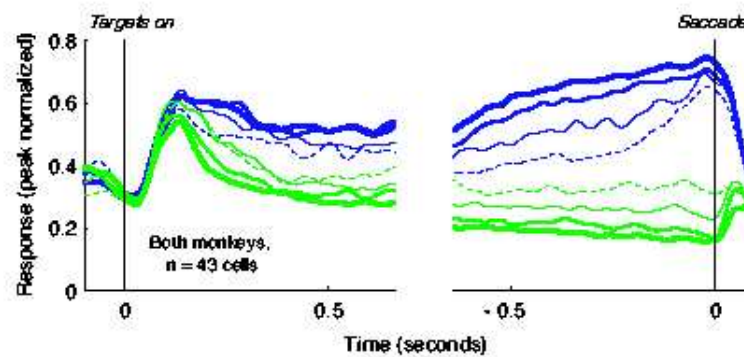
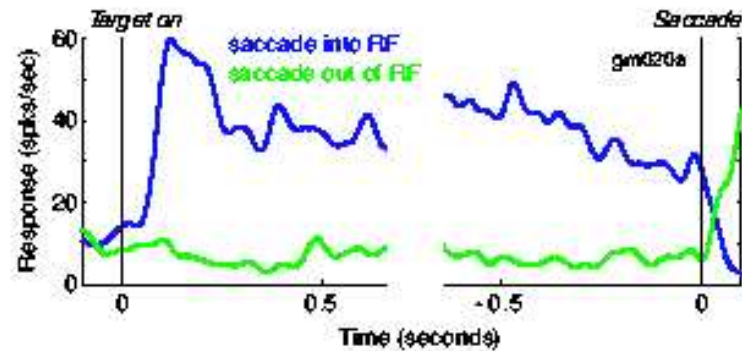
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Neurons in area LIP encode the local reward income.





Robustness

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Model is able to perform the task for different network parameters and different overall reward rates.



Robustness

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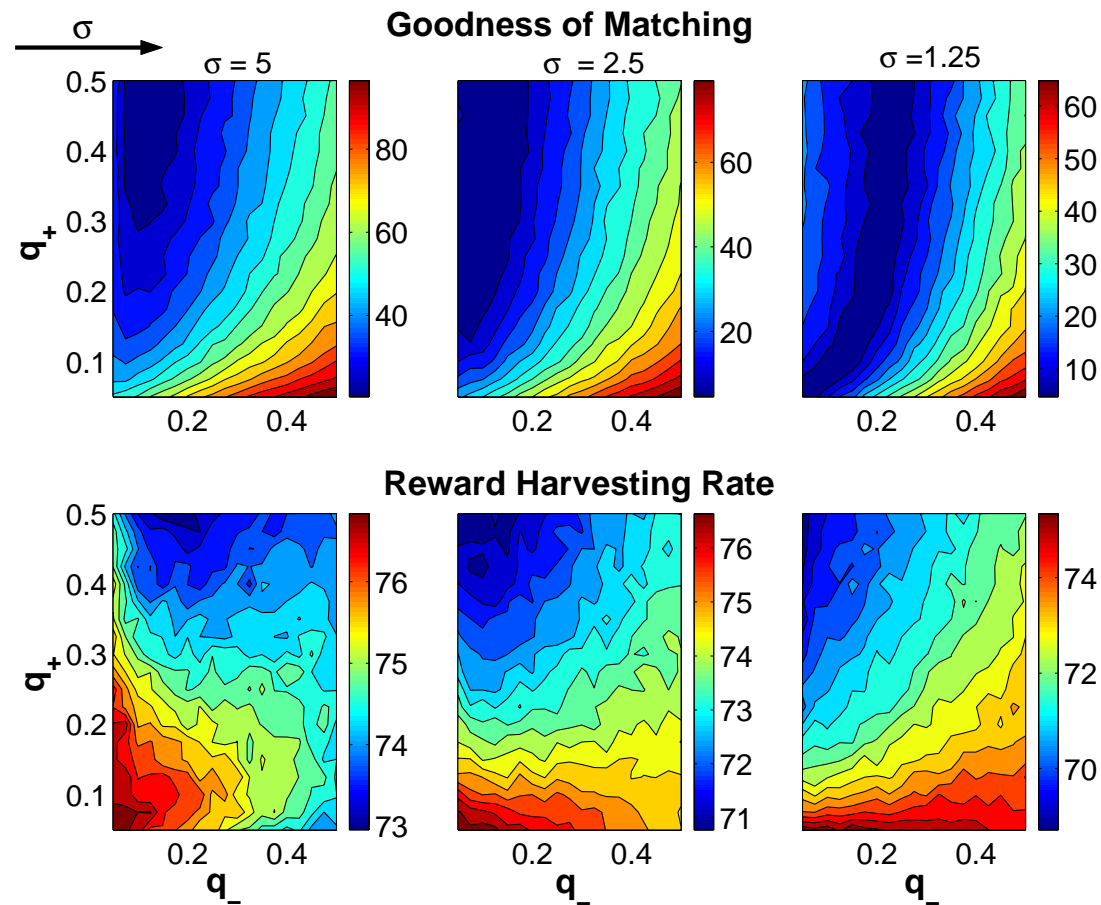
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Robustness

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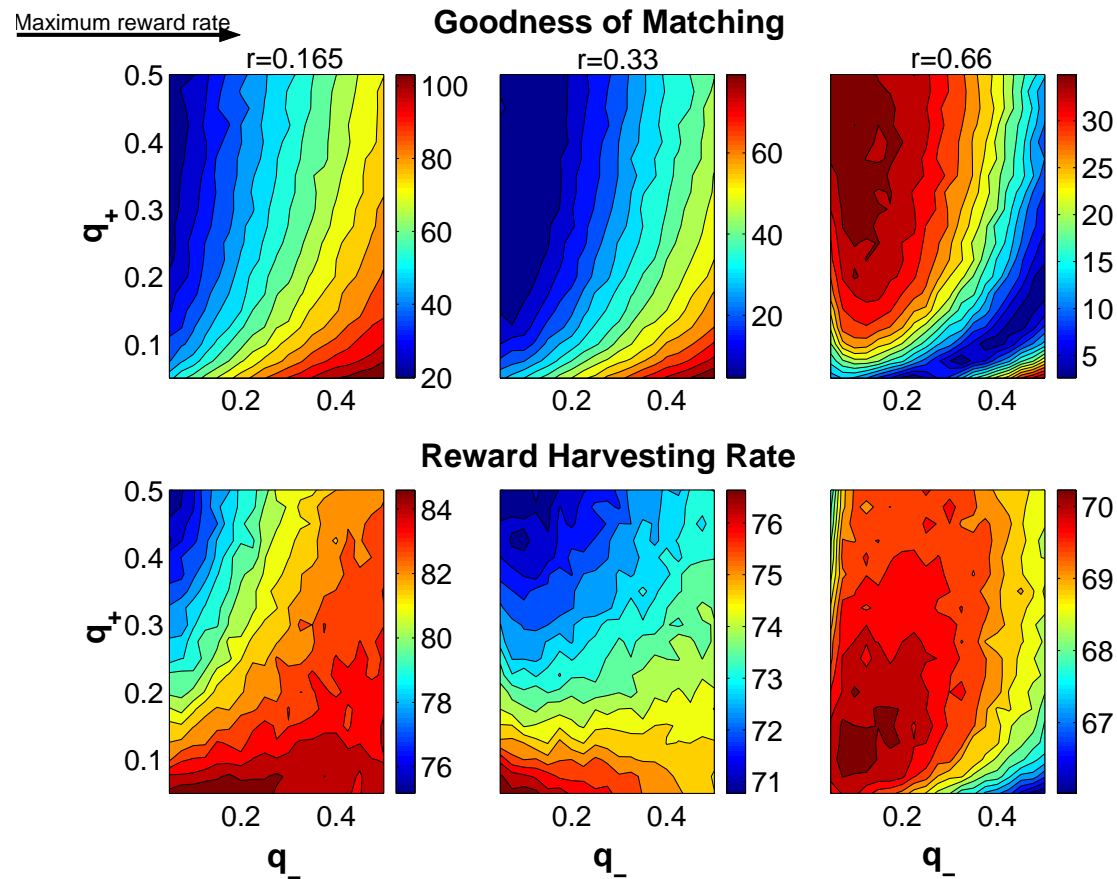
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Not so robust.



Type 1

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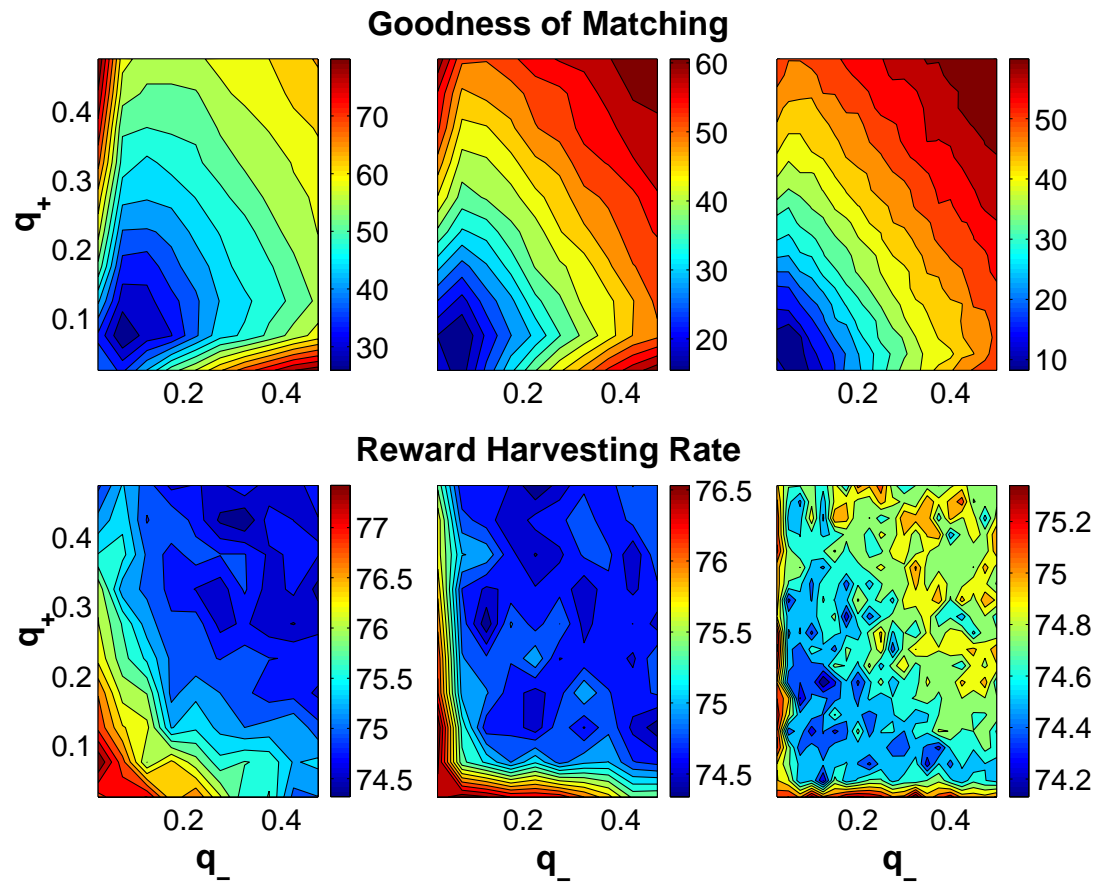
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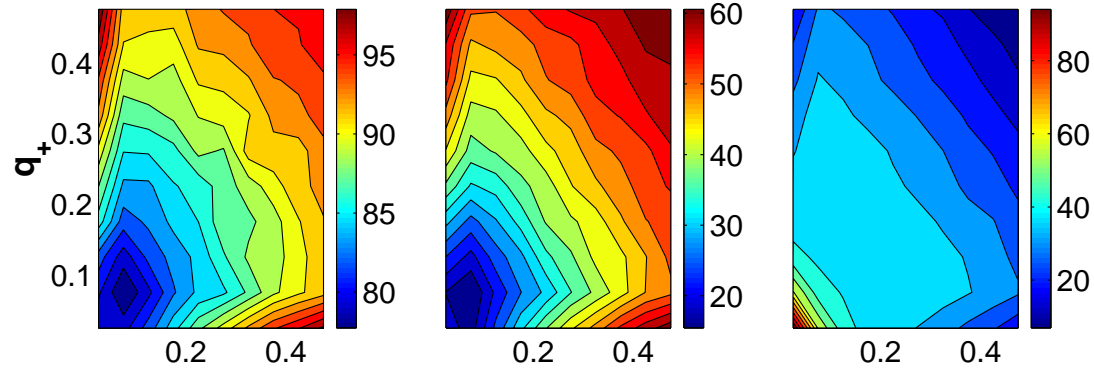
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Goodness of Matching



Reward Harvesting Rate

