

Adaptive Systems

Anil Seth
Informatics

Lectures 14 & 15: Neurorobotics

Neurorobotics

- ✦ Robots controlled by simulated nervous systems
- ✦ 'Brain based devices' (NSI, San Diego)
- ✦ Whisker-based models
- ✦ Hippocampal models
- ✦ Other stuff (if time).

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Neurorobotics

- ✦ A neurorobot has the following properties (Krichmar, 2008, *Scholarpedia*)
 - ✦ It engages in a behavioural task
 - ✦ It is situated in a real-world environment
 - ✦ It has a means to sense environmental cues and act upon its environment
 - ✦ Its behaviour is controlled by a simulated nervous system having a design that reflects, at some level, the brain's architecture and dynamics.
- ✦ Not enough simply to have 'neurons'!

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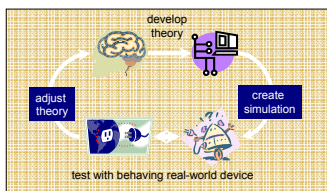
Neurorobotics

- ✦ Late 1980s: Kawato *et al.*: robotic devices testing theories of cerebellum.
- ✦ 1990s: Edelman *et al.*, The Neurosciences Institute: brain-based devices.
- ✦ Late 1990s: Many other groups.

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Brain-based devices



- ✦ Embodied morphology
- ✦ Neural simulation
- ✦ Value system

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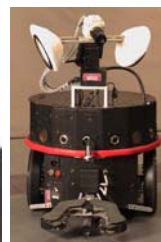
The Darwin series

Darwin IV-VI
1992 - 1998



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Darwin VII-VIII
1999 - 2002



Darwin IX-X
2003 - present



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Darwin VIII: The binding problem

- How do the functionally segregated areas of the brain coordinate their activities in order to associate various features of objects, and also distinguish among different objects?



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A possible solution

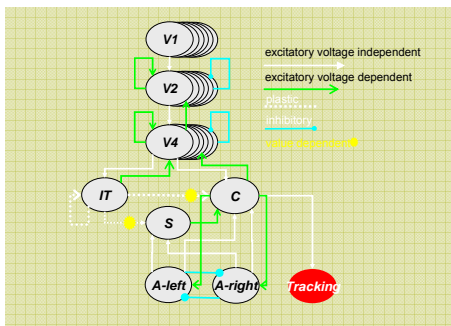
- Visual binding may result from the dynamic synchronization of neural activity brought about by reentrant connections among widely dispersed neural areas (Singer 1999).

- no need for any given region having superordinate control.
- synchrony can occur among groups of neurons rather than between pairs of individual neurons.
- specific neural timing relations and firing rates can act in a complementary fashion.

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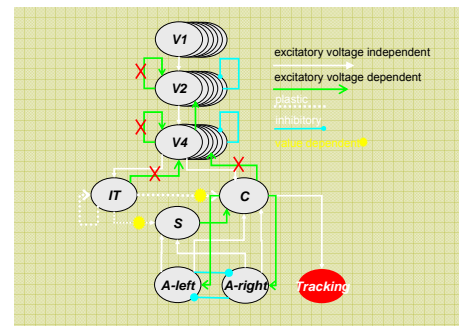
Darwin VIII neural simulation



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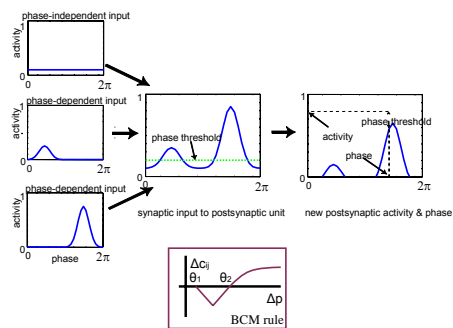
Darwin VIII neural simulation



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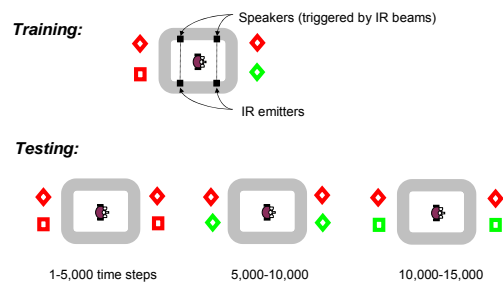
Neural dynamics



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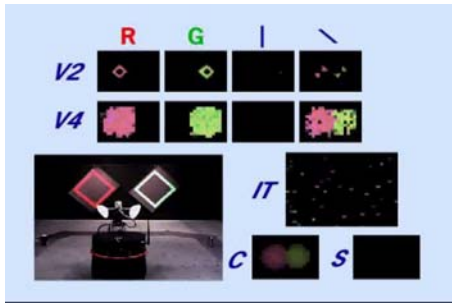
Experimental paradigm



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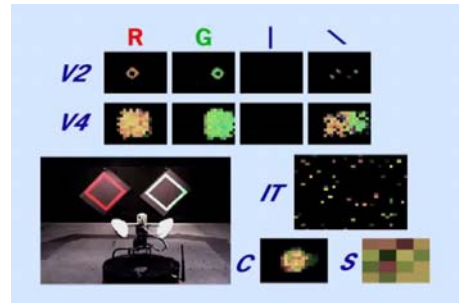
Behavior during training



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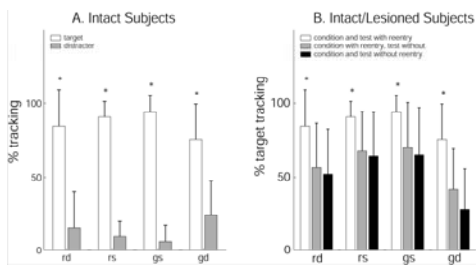
Behavior during testing



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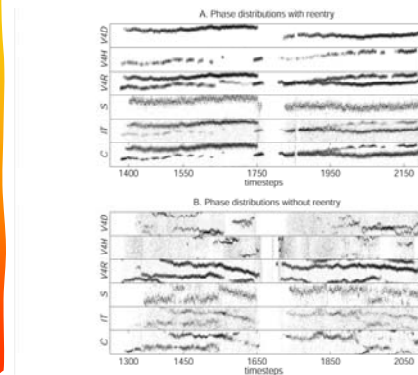
Performance is reduced following 'lesions' of reentrant connections



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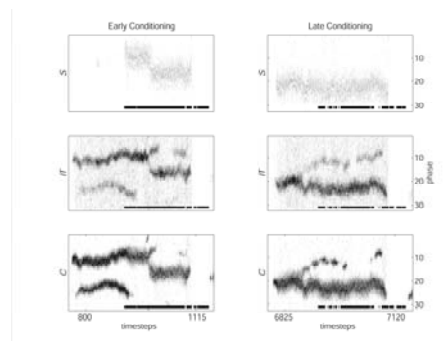
Phase responses after conditioning



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Neural dynamics of conditioning



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Darwin VIII: summary

- ✳ Darwin VIII discriminated and made selective movements in a real-world environment containing complex stimuli with overlapping features:
- ✳ Visual binding was achieved by the interaction of local and global processes.
 - No preferential directions of information flow.
 - No specialized superordinate areas.
- ✳ Success in this task depended on:
 - Constraints provided by its value system.
 - Reentrant signaling and synchronization among neuronal units.

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Whiskery robotics

- Whiskers are very widely used in the (non-human) animal world.
- They are used to discriminate texture; follow fish; detect, recognize, track and catch prey.

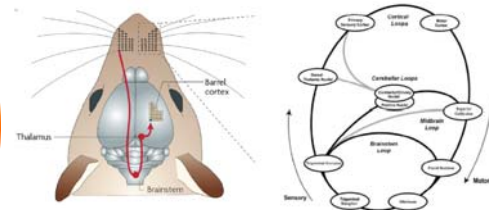


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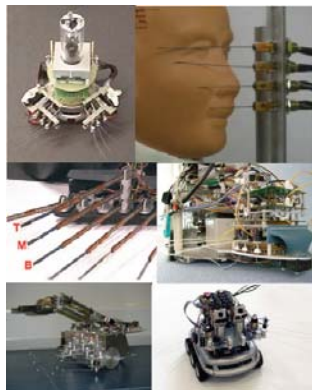
Whisker neuroanatomy

- Brain mechanisms of (rodent) whisker control and sensation are relatively well studied.



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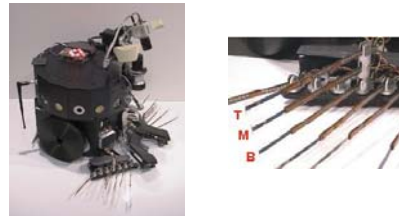


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Darwin IX

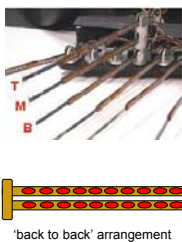
- Darwin IX is able to discriminate among textures in its environment and learns to avoid textures that are paired with aversive events.



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Darwin IX's whiskers



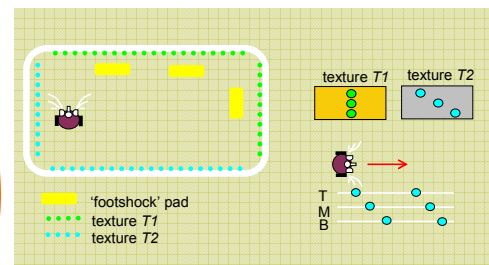
'back to back' arrangement

- Bending changes resistance
 - 0V (maximum deflection)
 - 5V (maximum deflection in opposite direction)
- Voltage converted to digital signal
 - Range from 0-255
 - Sample rate of 40Hz
- Each simulation cycle
 - 1 packet of 4 whisker values per whisker

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Darwin IX's environment

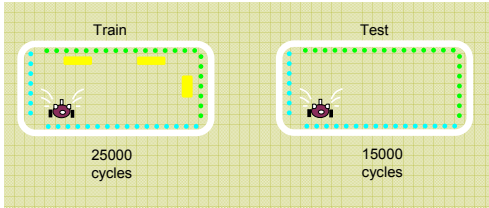


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Training and testing

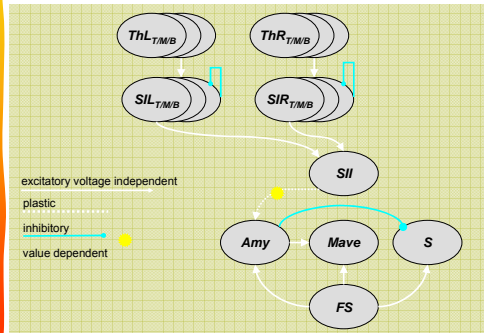
During training, either $T1$ or $T2$ were paired with foot-shock. During testing, the foot-shock pads were removed.



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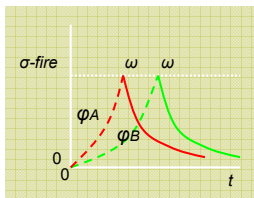
DXI simulated nervous system



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Neural dynamics ('lag cells')



Sub-regions of area Th contain 'lag-cells' which respond to whisker deflections with cell-specific delays.

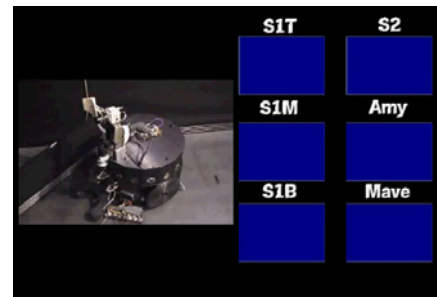
The figure shows 2 lag cells, A (red) and B (green).

--- internal state
— output

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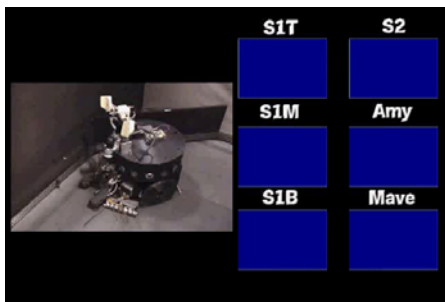
Behaviour and neural response to an aversive stimulus



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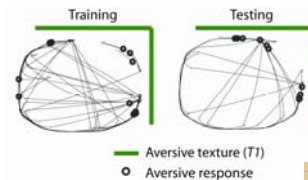
Behaviour and neural response to a neutral stimulus



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Darwin IX's behaviour



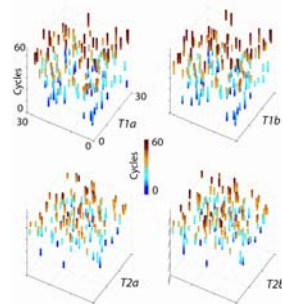
	$T1$	$T2$	Other
$T1$	96.6	2.2	1.2
$T2$	1.0	97.9	1.1

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SII neural activity

- ✦ Darwin IX's ability to categorize texture is supported by spatiotemporal patterns of activity in SII.
- ✦ Similar spatiotemporal receptive fields are observed in rat SI (Ghazanfar & Nicolelis, 1999; Shuler et al. 2001)



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Darwin IX Summary

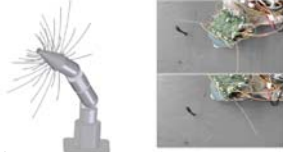
- ✦ Darwin IX uses whisker-based perception to categorize objects in its environment.
- ✦ Time-lagged responses to somatosensory input provide a plausible neural mechanism for texture discrimination.
- ✦ Approach illustrates a general mechanism for implementing spatiotemporal transformations.
- ✦ This mechanism, together with value dependent plasticity, provides a method for shaping actions based on haptic input.

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Whiskerbot

- ✦ 'Whiskerbot' uses a highly realistic mechanistic model of the rat whisker, coupled to a neural model of early sensory neurons.
- ✦ The robot is able to orient to stimuli, etc..



Pearson et al., (2005). Int. J. Adv. Rob. Sys

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Hippocampal neurorobotics

- ✦ Putting together the 'what', 'when' and 'where' of events.
- ✦ In humans, hippocampal activity is crucial for memory.

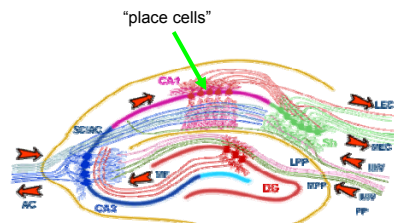


hippocampus actions.

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The hippocampus

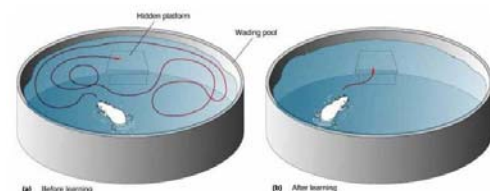


The Hippocampal Network: The hippocampus forms a principal and directional network, with input from the Entorhinal Cortex (EC) that forms connections with the Dentate Gyrus (DG) and CA3 pyramidal neurons via the Perforant Path (PP) - split into lateral and medial CA3 pyramidal neurons receive input from the DG via the Dentate Gyrus (DG). The output from CA3 pyramidal cells via the Schaffer Collateral Pathway (SCP), as well as to CA1 cells as the central area of hippocampus or the subiculum (SC). CA3 neurons also receive input directly from the Perforant Path and also of axons to the Subiculum Gyrus. These neurons in turn send the output to the subiculum (SC), forming a loop.

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Spatial memory in the Morris water maze



(a) Before learning

(b) After learning

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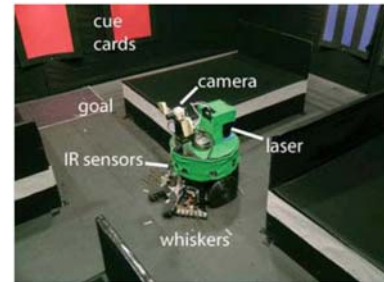
Morris water maze movies



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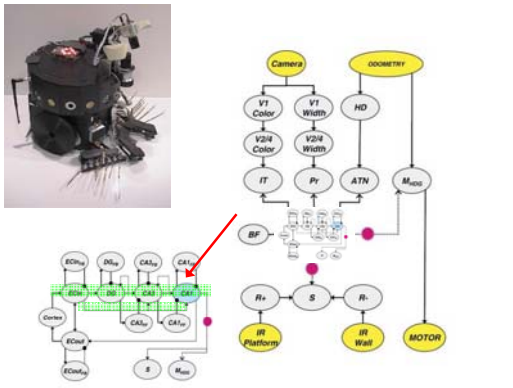
Darwin X



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Krichmar, J., Seth, A., et al. (2005). *Neuroinformatics* 3(3):197-222



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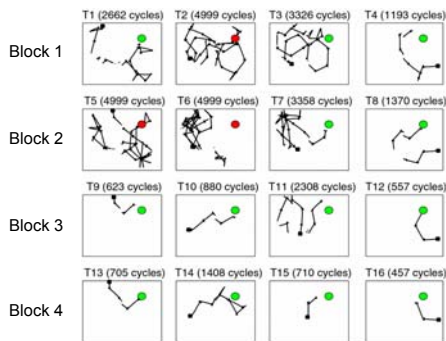
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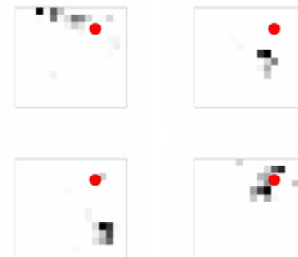
Typical training run



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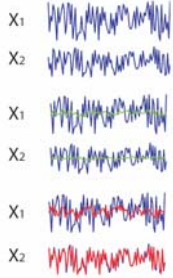
Representative Place Units (CA1)



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Granger causality



Causality based on prediction: If a signal X_1 causes a signal X_2 , then knowledge of the past of both X_1 and X_2 should improve the predictability of X_2 , as compared to knowledge of X_2 alone.

$$X_1(t) = \sum_{j=1}^m A_{11} X_1(t-j) + \sum_{j=1}^m A_{12} X_2(t-j) + \varepsilon_1(t)$$

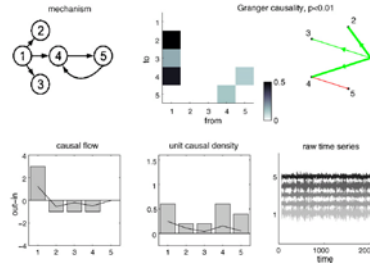
$$X_2(t) = \sum_{j=1}^m A_{21} X_1(t-j) + \sum_{j=1}^m A_{22} X_2(t-j) + \varepsilon_2(t)$$

If the variance of the prediction error ε_2 is significantly reduced by the inclusion of X_1 in the second equation, then we say that X_1 **Granger-causes** X_2 , and vice-versa.

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A MATLAB toolbox for Granger causal connectivity analysis
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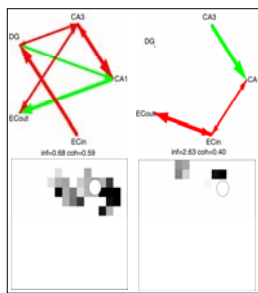


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Granger causality graphs

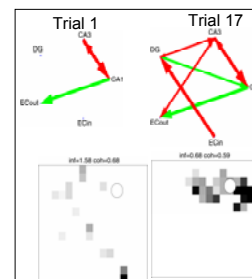
Tri-synaptic pathway Perforant pathway



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Causal connectivity before and after learning



→ One-way causality
↔ Reciprocal causality

CA1 cell 'place field'

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Causal connectivity before and after learning

Percentage of Causal Pathways

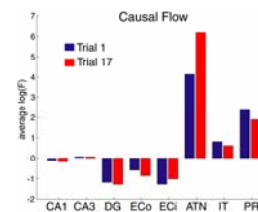
	Trial 1 (n=231)	Trial 17 (n=162)
Tri-synaptic	42.0	29.0
Perforant	14.8	21.6

- ✳ Proportion of tri-synaptic pathways *decreases* with experience.
- ✳ Proportion of perforant pathways *increases*.
- ✳ May reflect greater need for integration early in learning.

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Causality between hippocampus and cortical regions



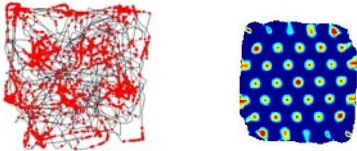
- ✳ Cortical regions are causing or driving the hippocampus
- ✳ Hippocampal regions tend to be driven or balanced

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Other hippocampal approaches

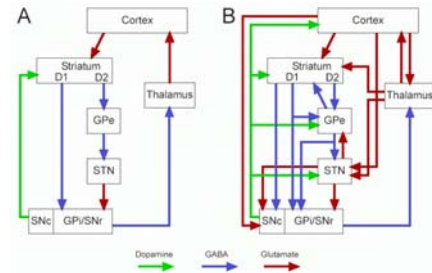
- Arleo & Gerstner (1997, 2000, etc.): Place cell models can support navigation.
- Cuperlier & Gaussier (2005, 2007, etc.): Introduction of 'transition cells'
- Samu et al. (!): Grid cells.



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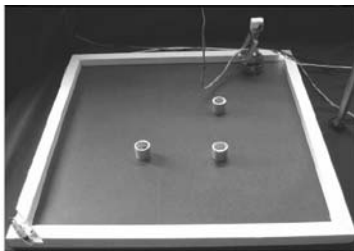
Basal ganglia neurorobotics



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Basal ganglia neurorobotics



Prescott, Gurney, Redgrave (2000 onwards)

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Other avenues

- Motor control based on neural models of central pattern generators (Ijspeert et al., 2007).
- Models of 'mirror neuron' systems for imitation (Arbib and Rizzolati, 1998)
- Cerebellar models (e



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Summary

- Neurobotics provides a rich resource for the design of adaptive robotics.
- Analysis of neurobots provides useful heuristics for interpreting neuroscience data.
- Neurobotics for science vs. neurobotics for engineering.
- Future directions: neuromorphic chips, SLAM, flexible morphologies, etc.

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Further reading

- Krichmar, J. (2008). Neurobotics. *Scholarpedia* 3(3):1365.
- Krichmar, J. & Edelman, G.M. (2002). Machine psychology: autonomous behavior, perceptual categorization and conditioning in a brain-based device. *Cerebral Cortex* 12:818-830.
- Seth, A.K., et al. (2005). Neurobotic models in neuroscience and neuroinformatics. *Neuroinformatics*, 3(3)
- Seth, A.K., et al. (2004). Visual binding through reentrant connectivity and dynamic synchronization in a brain-based device. *Cerebral Cortex*, 14:1185-99.
- Banquet et al. (2005). A hierarchy of associations in hippocampal-cortical systems. *Neural Computation* 17:1339-1384.
- Kaplan, F. (2008). Neurobotics: An experimental science of embodiment. *Frontiers in Neurobotics* 2(1):22-3
- Prescott, T. et al. (2006). A robot model of the basal ganglia: behaviour and intrinsic processing. *Neural Networks* 19(1):31-61

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