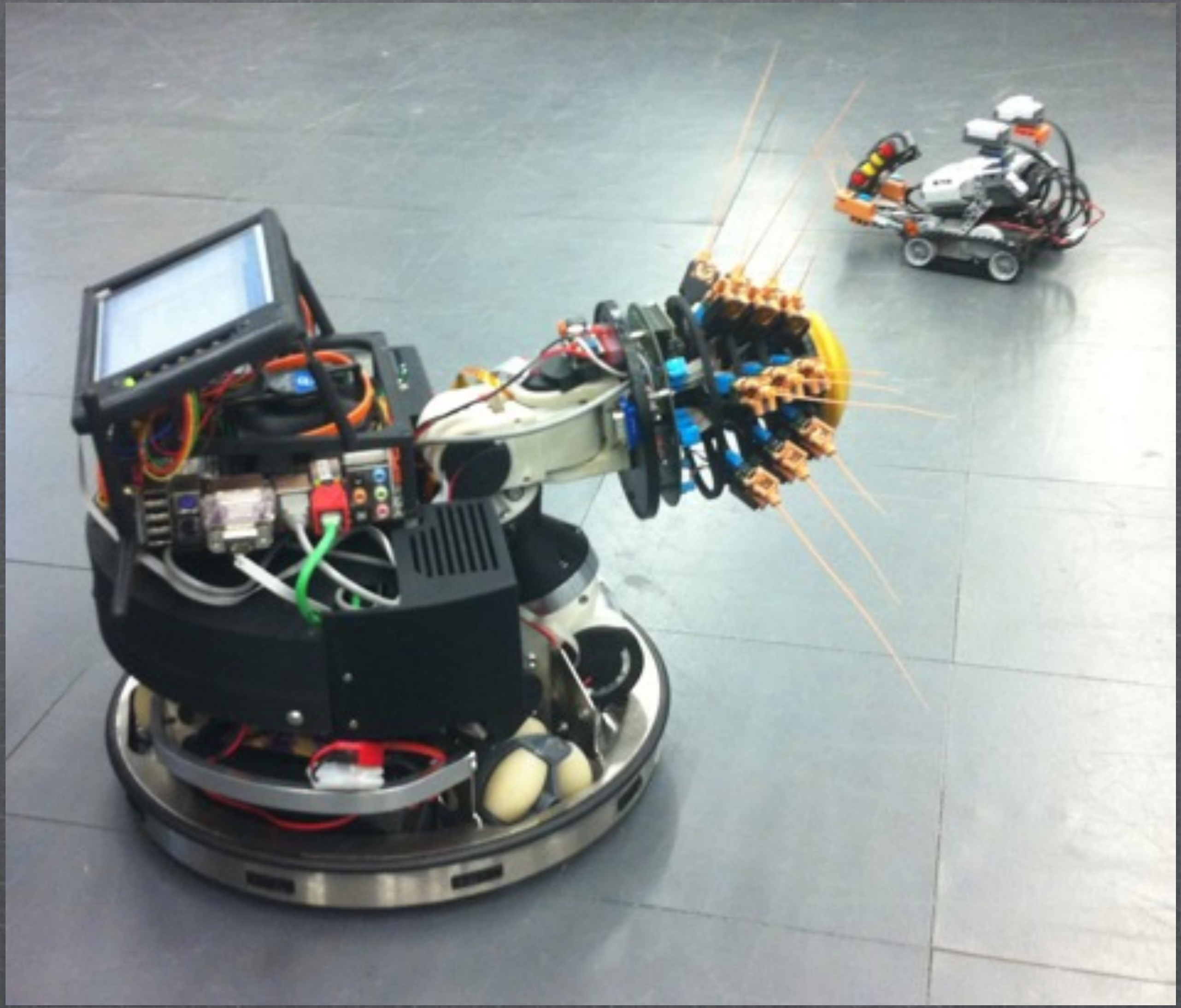
LAYERED CONTROL ARCHITECTURES IN MAMMALS ANDS ROBOTS

CBMM SUMMER SCHOOL, WOODSHOLE 2015



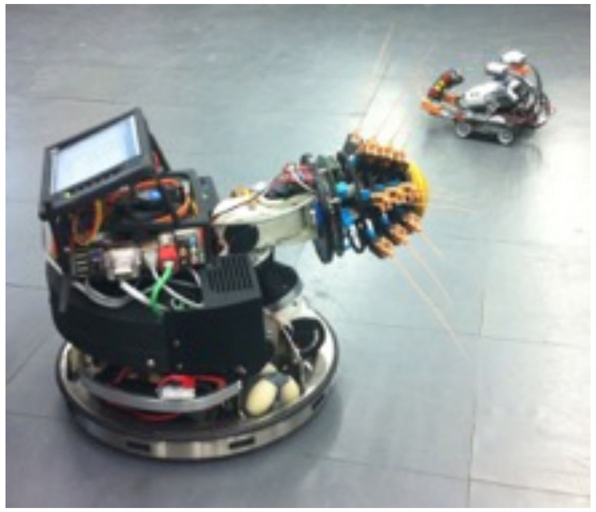
The University Of Sheffield.

Tony Prescott
University of Sheffield

SHEFFIELD ROBOTICS

THEMES

BIOMIMETICS



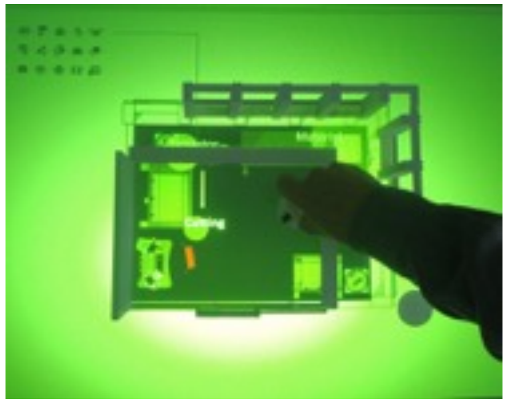
COGNITIVE ROBOTICS

SWARM ROBOTICS

FLEXIBLE MANUFACTURING

FIELD ROBOTICS

MIXED-REALITY & TELEPRESENCE



ASSISTIVE ROBOTICS

COMPANION ROBOTICS

SHEFFIELD ROBOTICS

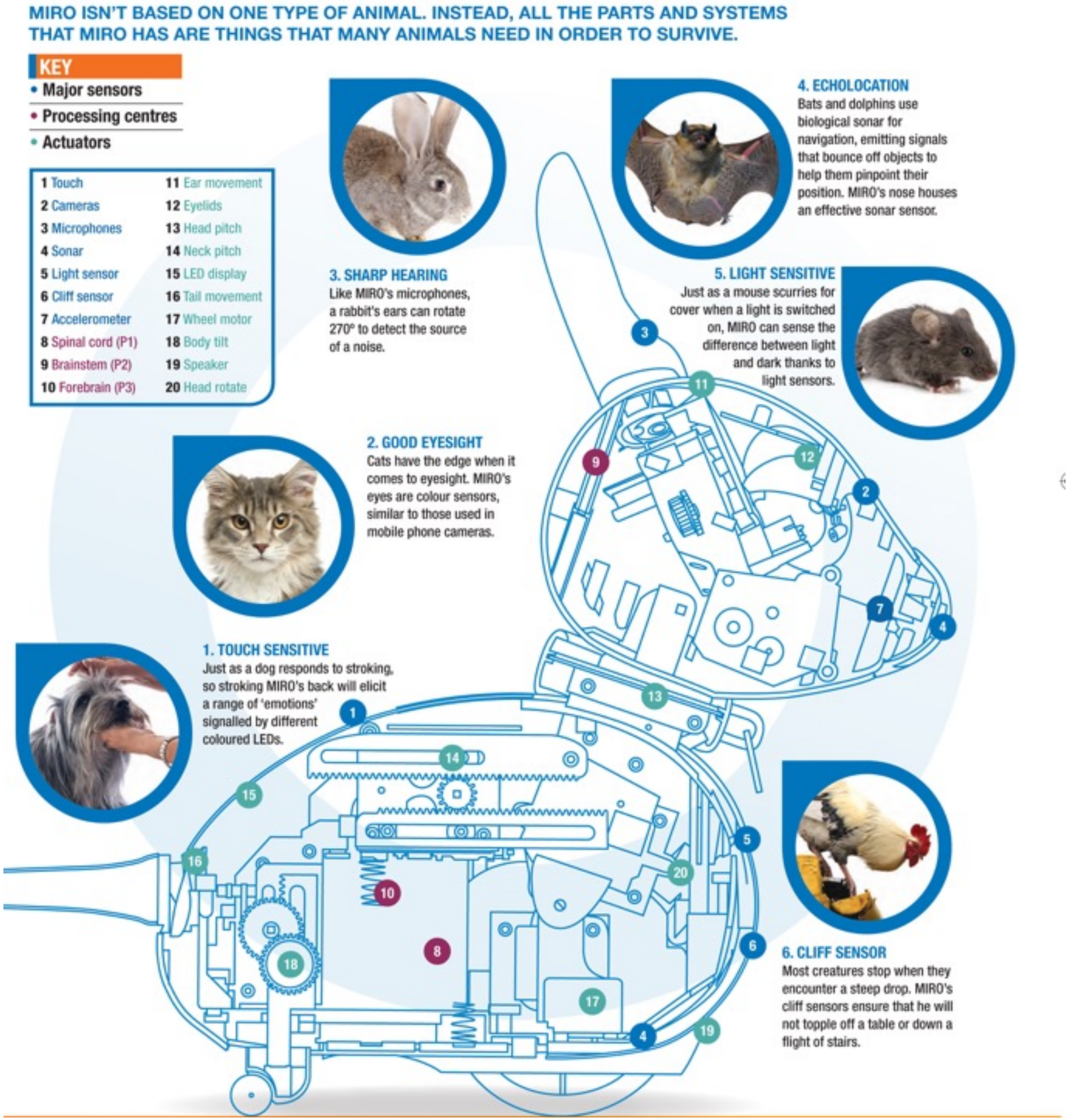
www.sheffieldrobotics.ac.uk

MiRO is not based on any one animal but has some general Mammalian characteristics

13 DOFs

3 ARM processors

Sensors:
Binocular vision (2x640x480)
Binaural hearing
Infrared
Ultrasound
Touch



MIRO ISN'T BASED ON ONE TYPE OF ANIMAL. INSTEAD, ALL THE PARTS AND SYSTEMS THAT MIRO HAS ARE THINGS THAT MANY ANIMALS NEED IN ORDER TO SURVIVE.

KEY
- Major sensors
- Processing centres
- Actuators

1 Touch
2 Cameras
3 Microphones
4 Sonar
5 Light sensor
6 Cliff sensor
7 Accelerometer
8 Spinal cord (P1)
9 Brainstem (P2)
10 Forebrain (P3)
11 Ear movement
12 Eyelids
13 Head pitch
14 Neck pitch
15 LED display
16 Tail movement
17 Wheel motor
18 Body tilt
19 Speaker
20 Head rotate

1. TOUCH SENSITIVE
Just as a dog responds to stroking, so stroking MIRO's back will elicit a range of 'emotions' signalled by different coloured LEDs.

2. GOOD EYESIGHT
Cats have the edge when it comes to eyesight. MIRO's eyes are colour sensors, similar to those used in mobile phone cameras.

3. SHARP HEARING
Like MIRO's microphones, a rabbit's ears can rotate 270° to detect the source of a noise.

4. ECHOLOCATION
Bats and dolphins use biological sonar for navigation, emitting signals that bounce off objects to help them pinpoint their position. MIRO's nose houses an effective sonar sensor.

5. LIGHT SENSITIVE
Just as a mouse scurries for cover when a light is switched on, MIRO can sense the difference between light and dark thanks to light sensors.

6. CLIFF SENSOR
Most creatures stop when they encounter a steep drop. MIRO's cliff sensors ensure that he will not topple off a table or down a flight of stairs.

THE PROBLEM OF BEHAVIOURAL INTEGRATION

“the phenomenon so very characteristic of living organisms, and so very difficult to analyze: **the fact that they behave as wholes rather than as the sum of their constituent parts. Their behavior shows integration,** […] a process unifying the actions of an organism into patterns that involve the whole individual.”

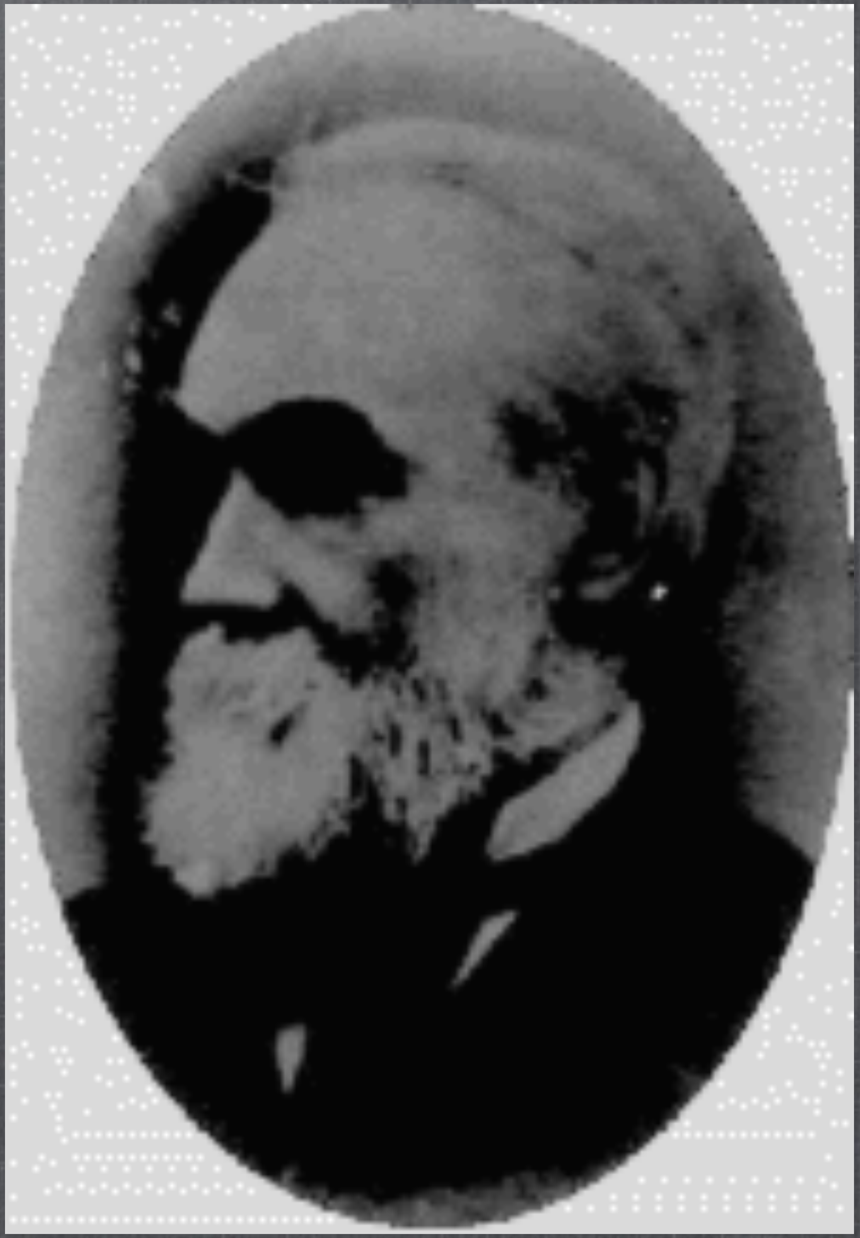
(Barrington, 1967, p. 415)

Courtesy of Ed Sweeney. License CC BY.

ORGANISING PRINCIPLES I.
THE BRAIN AS A LAYERED ARCHITECTURE

"That the middle motor centers represent over again what all the lowest motor centers have represented, will be disputed by few. I go further, and say that the highest motor centers (frontal lobes) represent over again, in more complex combinations, what the middle motor centers represent."

From "The evolution and dissolution of the nervous system" (1884)



John Hughlings Jackson
1835-1911

TRANSECTION STUDIES

Diencephalic rat—

generates motivated sequences

Midbrain rat—

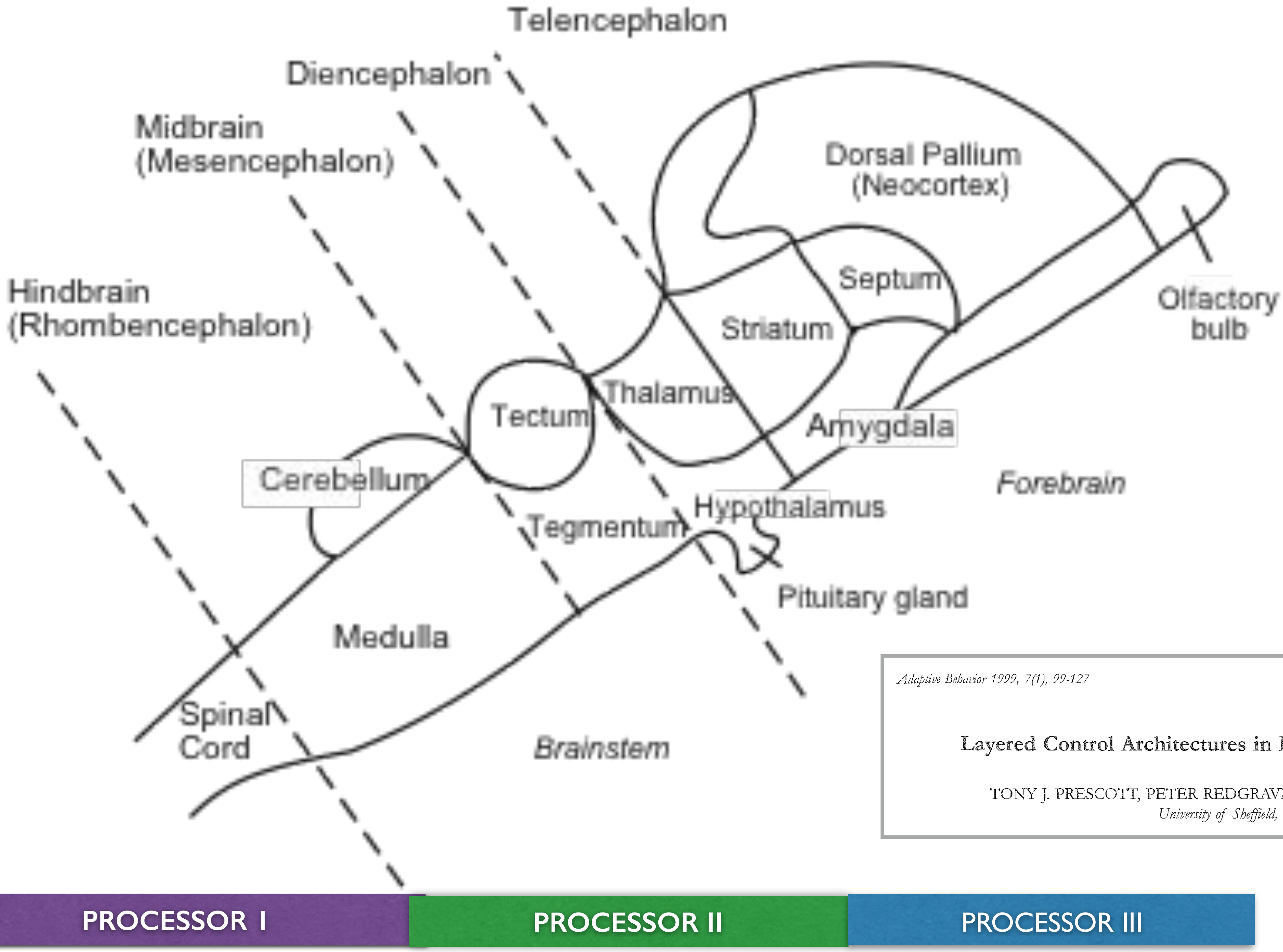
Capacity for individual actions

Hindbrain rat—

Component movements spared

Figure removed due to copyright restrictions. Please see the video.

MiRo has a layered control architecture modelled on the



Adaptive Behavior 1999, 7(1), 99-127

Layered Control Architectures in Robots and Vertebrates

TONY J. PRESCOTT, PETER REDGRAVE, AND KEVIN GURNEY
University of Sheffield, UK

Source: Prescott, Tony J., Peter Redgrave, and Kevin Gurney. "Layered control architectures in robots and vertebrates." Adaptive Behavior 7, no. 1 (1999): 99-127.

ORGANISING PRINCIPLES II.
A CENTRAL INTEGRATIVE CORE

A group of central, sub-cortical brain structures serves to coordinate and integrate the activity of both higher- (cortical) and lower-level neural systems.

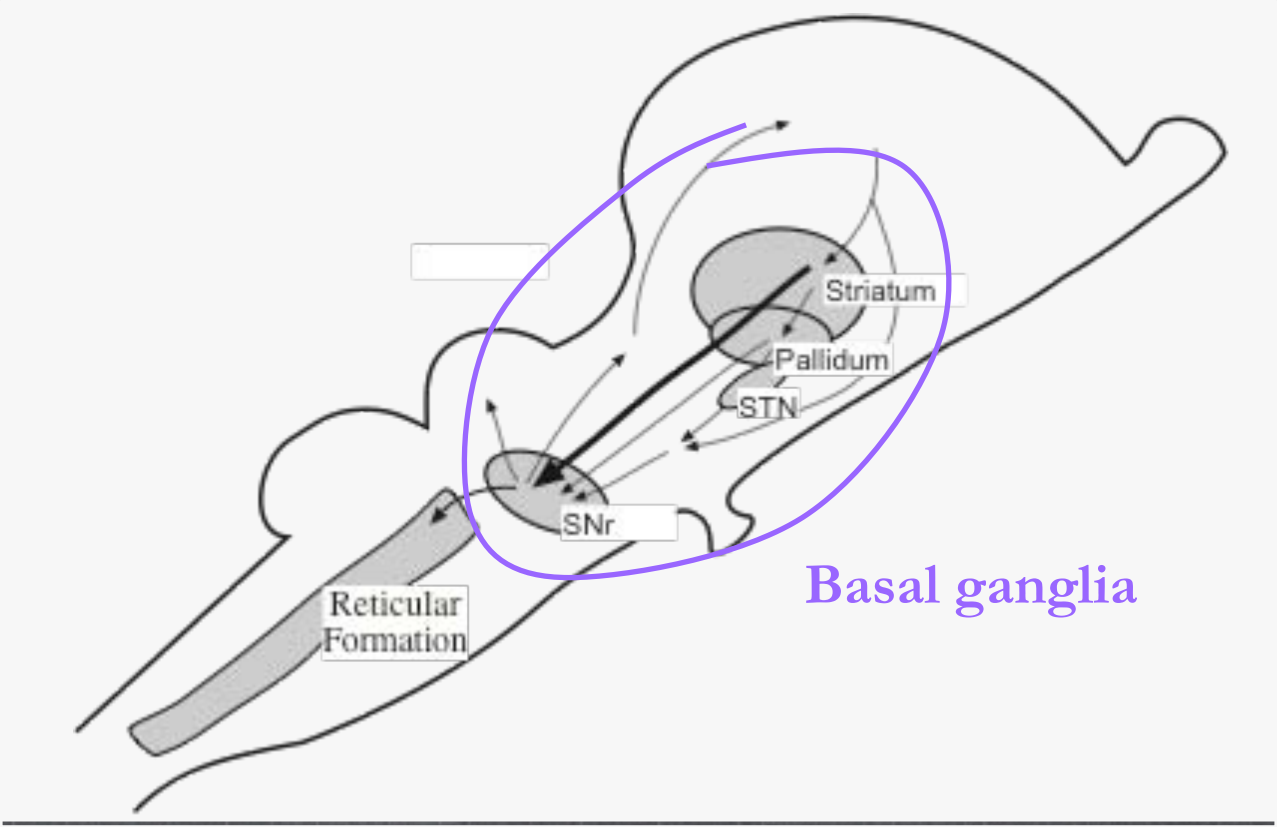


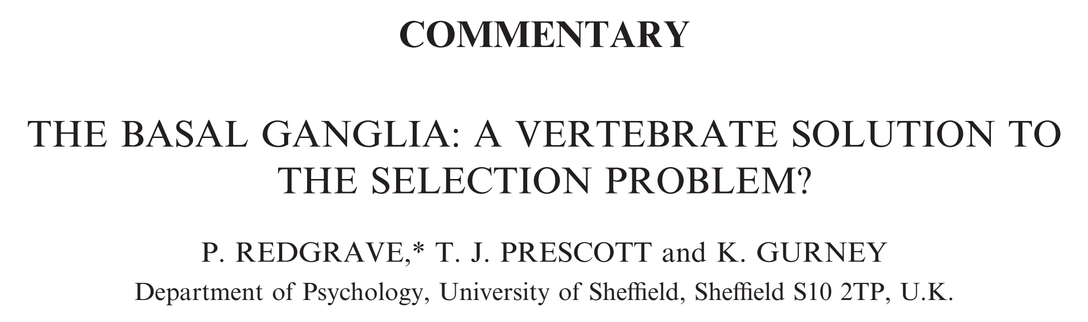
Image of Wilder Penfield removed due to copyright restrictions. Please see the video.

Source: Medina, Loreta, and Anton Reiner. "Neurotransmitter Organization and Connectivity of the Basal Ganglia in Vertebrates: Implications for the Evolution of Basal Ganglia (Part 1 of 2)." Brain, behavior and evolution 46, no. 4-5 (1995): 235 246.

This notion is captured in the notion of a *centrencephalic* dimension to nervous system organization

THE VERTEBRATE BASAL GANGLIA— A SPECIALISED ACTION SELECTION MECHANISM

Figure of the vertebrate brain removed due to copyright restrictions. Please see the video.

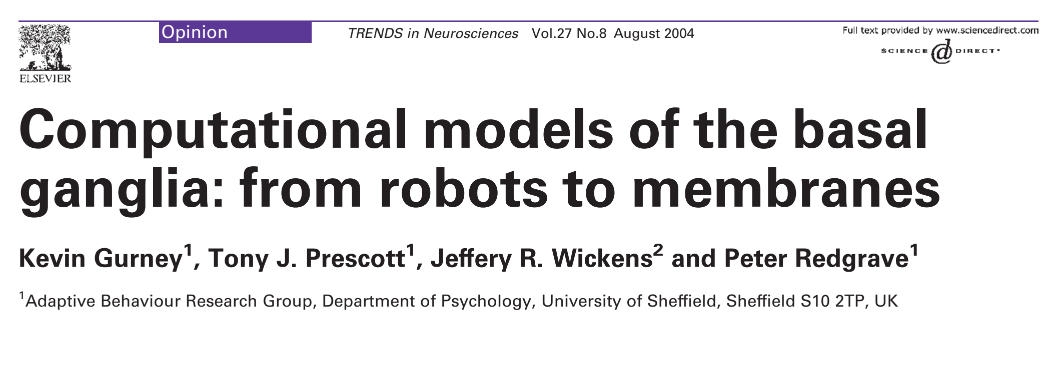


COMMENTARY

THE BASAL GANGLIA: A VERTEBRATE SOLUTION TO THE SELECTION PROBLEM?

P. REDGRAVE,* T. J. PRESCOTT and K. GURNEY

Department of Psychology, University of Sheffield, Sheffield S10 2TP, U.K.



ELSEVIER

Opinion

TRENDS in Neurosciences Vol.27 No.8 August 2004

Full text provided by www.sciencedirect.com

SCIENCE DIRECT

Computational models of the basal ganglia: from robots to membranes

Kevin Gurney[1], Tony J. Prescott[1], Jeffery R. Wickens[2] and Peter Redgrave[1]

[1]Adaptive Behaviour Research Group, Department of Psychology, University of Sheffield, Sheffield S10 2TP, UK

BASAL GANGLIA INPUT— BRANCHED PATHWAYS FROM SENSORIMOTOR SYSTEMS

Figure of the vertebrate brain removed due to copyright restrictions. Please see the video.

Functional systems specifying action are widely distribute throughout the neuraxis. The striatum receives input from most of the cortex, the limbic system, and motor areas of the brainstem

BASAL GANGLIA OUTPUT—
DISINHIBITORY CONTROL OVER MOVEMENT GENERATORS

Figure of the vertebrate brain removed due to copyright restrictions. Please see the video.

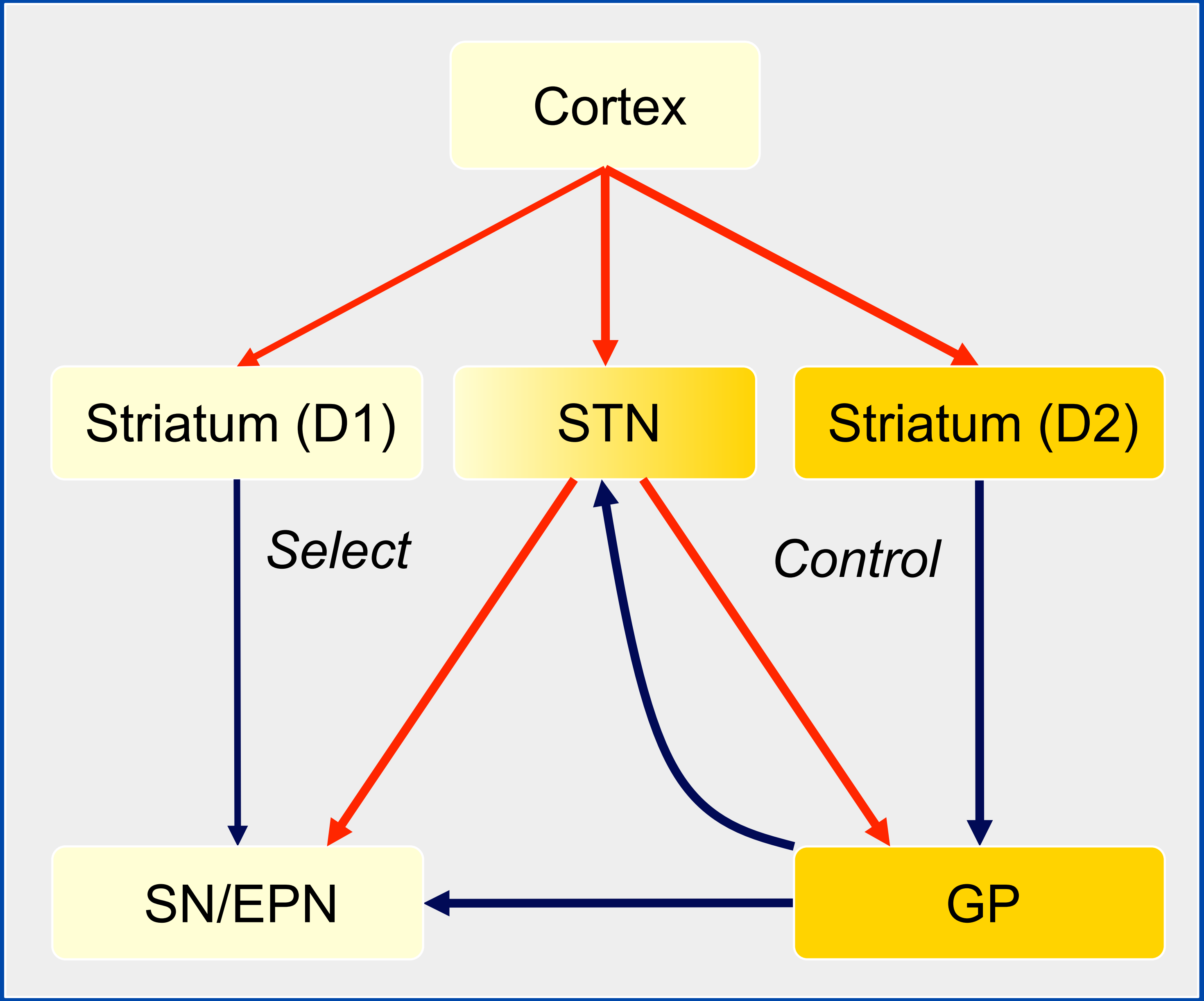
Main *output* centers are *tonically active* and direct a continuous flow of *inhibition* at centers throughout the brain that directly or indirectly generate movement

Computational models at the systems level

We have developed (Gurney et al, 1998) a computational model of the basal ganglia viewed as two functional subsystems— a selection subsystem and a control subsystem.

Cell populations are modelled as leaky integrators with piecewise linear output

Shown to implement an optimal test for decision-making the **Multiple Sequential Probability Ratio Test** (MSPRT), Bogacz & Gurney, 2007



Cortex

Striatum (D1)

STN

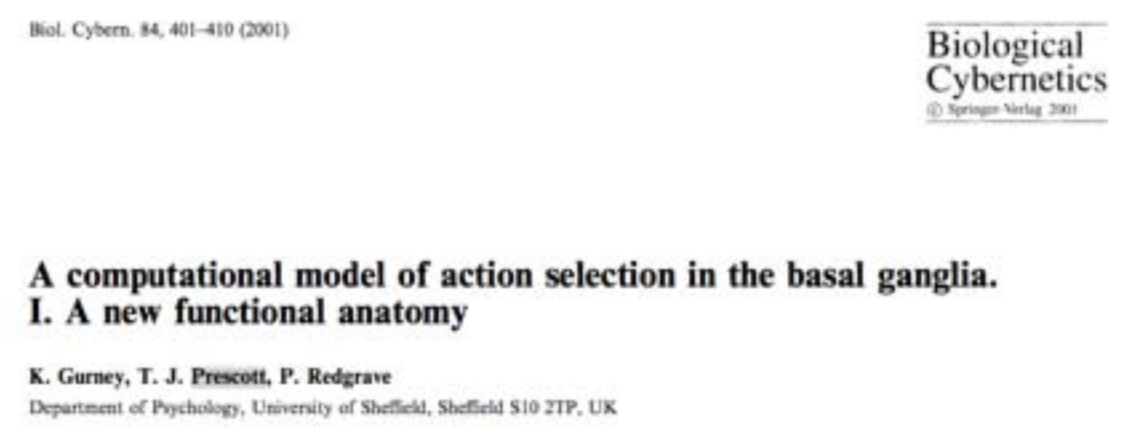
Striatum (D2)

Select

Control

SN/EPN

GP



Biol. Cybern. 84, 401–410 (2001)

Biological Cybernetics
© Springer-Verlag 2001

**A computational model of action selection in the basal ganglia.
I. A new functional anatomy**

K. Gurney, T. J. Prescott, P. Redgrave
Department of Psychology, University of Sheffield, Sheffield S10 2TP, UK

Developing a robot model— building the robot/model interface

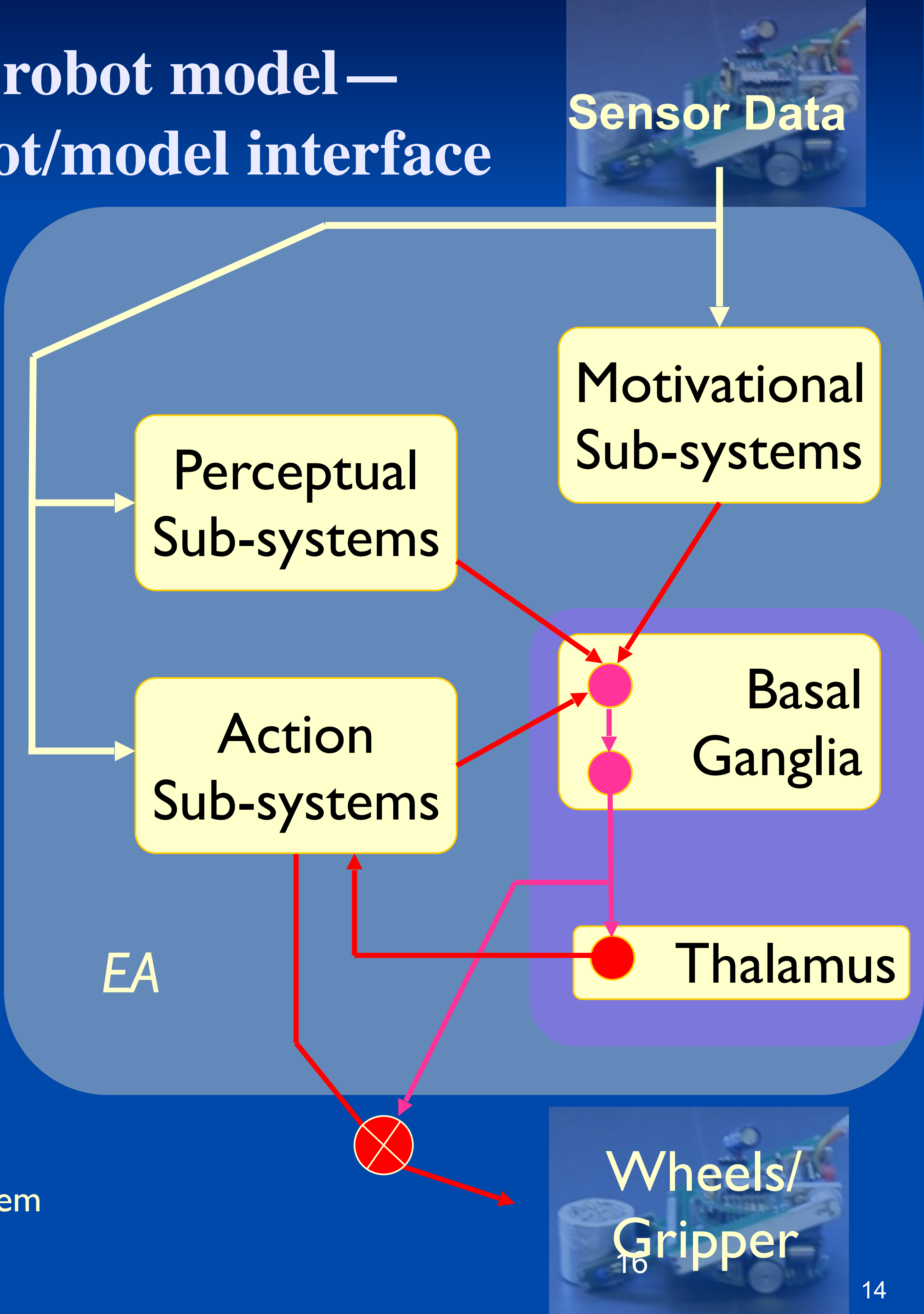
Extrinsic Variables

1) Perceptual sub-systems
(Wall, corner, can, gripper)

Intrinsic Variables

2) Motivational sub-systems
(Fear, Hunger)

3) Action sub-systems/current state
(Wall seek, wall follow, can
seek, can pick-up, can deposit)



Sensor Data

Motivational Sub-systems

Perceptual Sub-systems

Basal Ganglia

Action Sub-systems

Thalamus

EA

Wheels/ Gripper

At each time step:

Basal ganglia/thalamus

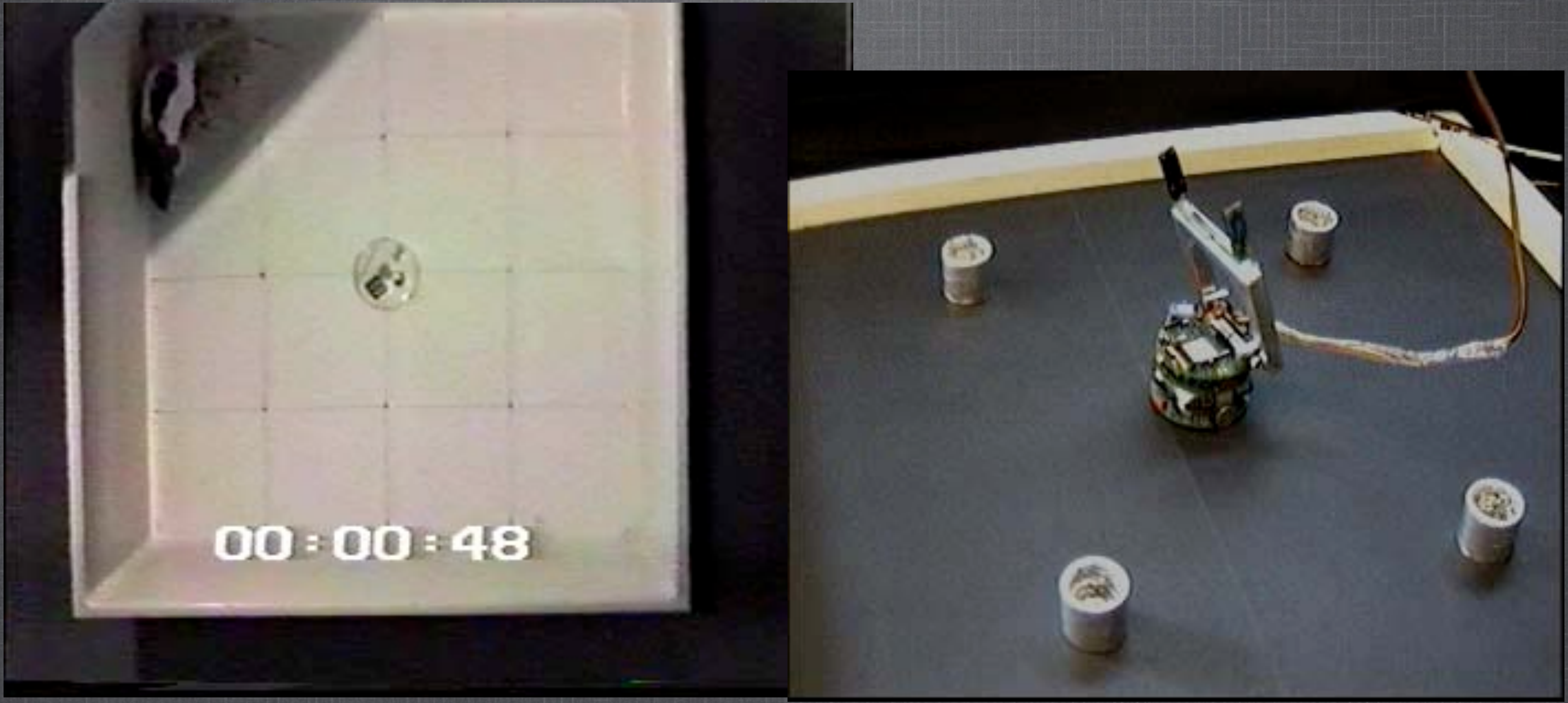
- Computes saliences
- Resolves competition
- Disinhibits winning sub-system

HUNGRY RAT IN AN OPEN FIELD ARENA

Source: Prescott, Tony J., Fernando M. Montes González, Kevin Gurney, Mark D. Humphries, and Peter Redgrave. "A robot model of the basal ganglia: Behavior and intrinsic processing." Neural Networks 19, no. 1 (2006): 31-61.

BEHAVIOURAL SEQUENCING IN A ROBOT MODEL

Prescott et al. 2006 *Neural Networks*



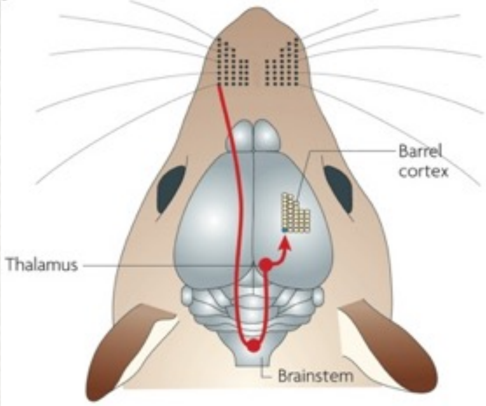
Source: Prescott, Tony J., Fernando M. Montes González, Kevin Gurney, Mark D.Humphries, and Peter Redgrave. "A robot model of the basal ganglia: Behavior and intrinsic processing." Neural Networks 19, no. 1 (2006): 31-61.

EXPLORING BRAIN ARCHITECTURE THROUGH ACTIVE TOUCH

- Used by the rat to control orienting, to extract shape and texture, and to maintain balance
- Interesting parallels with human fingertips
- Uses structures and pathways at all levels of the neuraxis
- Therefore a good model system in which to try and understand the **general principles of mammalian active touch**

Real-time

Sensorimotor loops for vibrissal control

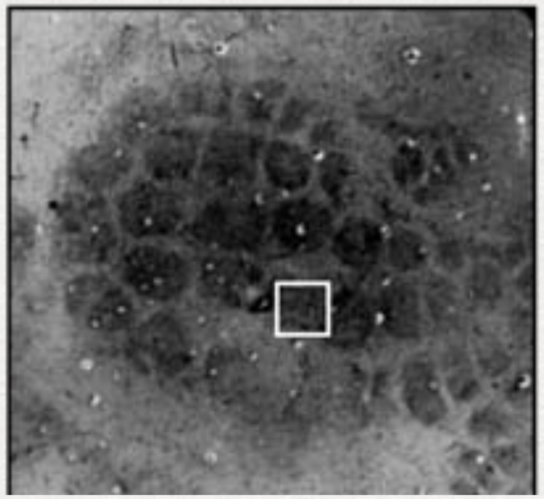


Reprinted by permission from Macmillan Publishers Ltd: Nature Reviews Neuroscience.
Source: Diamond, Mathew E., Moritz Von Heimendahl, Per MagneKnutsen, David Kleinfeld, and Ehud Ahissar. "'Where'and'what'in the whisker sensorimotor system." Nature Reviews Neuroscience 9, no. 8 (2008): 601-612. © 2008.

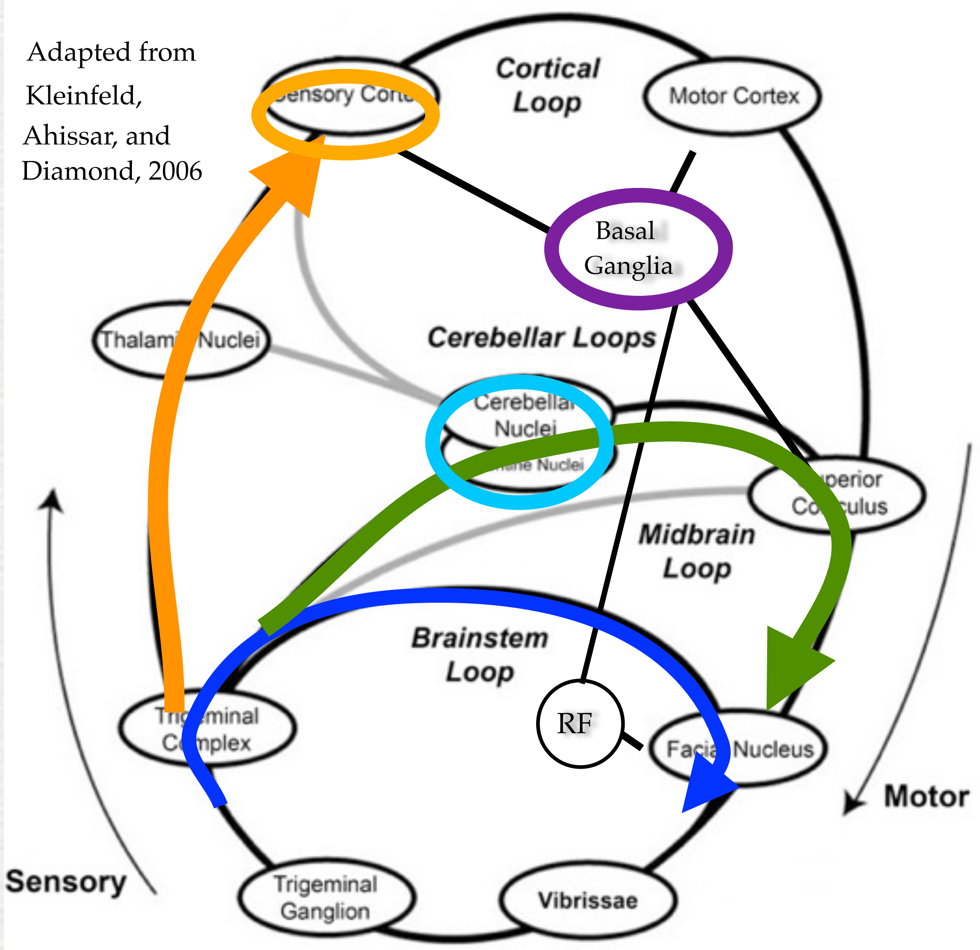
From Diamond et al. 2008

Image of a rat brain removed due to copyright restrictions. Please see the video.

http://www.nibb.ac.jp/brish/Gallery/cortexE.html



Wilson, Stuart P., Judith S. Law, Ben Mitchinson, Tony J. Prescott, and James A. Bednar. "Modeling the emergence of whisker direction maps in rat barrel cortex." PloS one 5, no. 1 (2010): e8778. https://doi.org/10.1371/journal.pone.0008778. License CC BY.



Adapted from Kleinfeld, Ahissar, and Diamond, 2006

Source: Kleinfeld, David, Ehud Ahissar, and Mathew E. Diamond. "Active sensation: Insights from the rodent vibrissa sensorimotor system." Current opinion in neurobiology 16, no. 4 (2006): 435-444.

WHISKING WITH ROBOTS

Prescott et al.. *IEEE Robotics and Automation Magazine*, Sept. 2009
Pearson, et al.. *Philosophical Trans B*. 2011

Actuated whisker (2003)
Fiber-glass whisker
Shape-memory alloy actuator
Strain-gauge transducers
Electro-mechanical model of transduction

Whiskerbot (2004-2006)
2x3 1-DOF Whisker array
Feedback-modulated whisker pattern generation
2-d orient-to-stimulus model
Texture discrimination

Scratchbot (2006-2009)
2x3x3 3-DOF Whisker arrays,
Hall-effect transducers
3-d orient-to-stimulus
Noise cancellation
Tactile-guided exploration

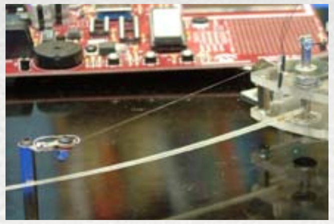
Biotact sensor (2008-2012)
Modular awhisker design
Feature-extraction
Classifiers for active touch
Self-organising feature maps

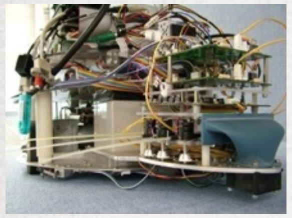
Shrewbot (2011-2013)
Modular actuated whisker design
Improved morphology
Better maneurability
Tactile SLAM
Predator-prey model

Goosebot (2012-2013)
Linear actuation of rows to simulate deformable mystacial pad
Tactile salience model

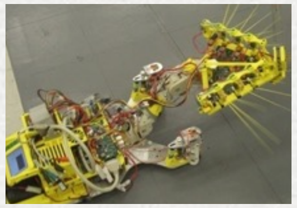
EAP Whisker (2014-)
Novel design for muscle-like EAP actuator
New cerebellar model
Tareq Assaf
Demo today, 4.30
talk Thursday, 4.30

Funding: EPSRC, EU FP6 ICEA, EUFP7 BIOTACT

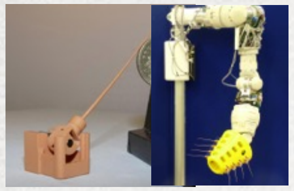


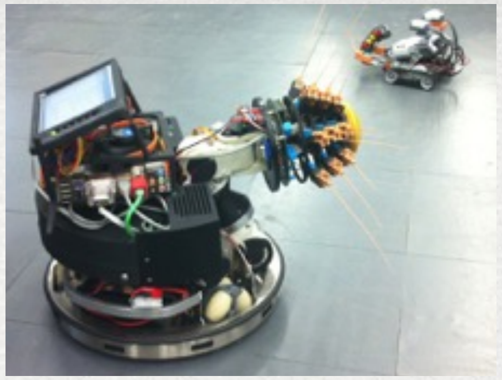


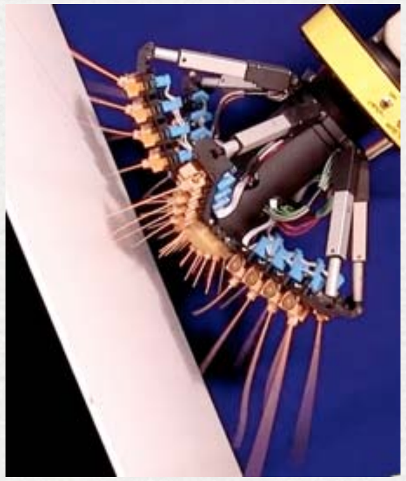
Source: Pearson, Martin J., Anthony G. Pipe, Chris Melhuish, Ben Mitchinson, and Tony J. Prescott. "Whiskerbot: a robotic active touch system modeled on the rat whisker sensory system." Adaptive Behavior 15, no. 3 (2007): 223-240.



Source: Prescott, Tony J., Martin J. Pearson, Ben Mitchinson, J. Charles W. Sullivan, and Anthony G. Pipe. "Whisking with robots." IEEE robotics & automation magazine 16, no. 3 (2009).







WHISKING

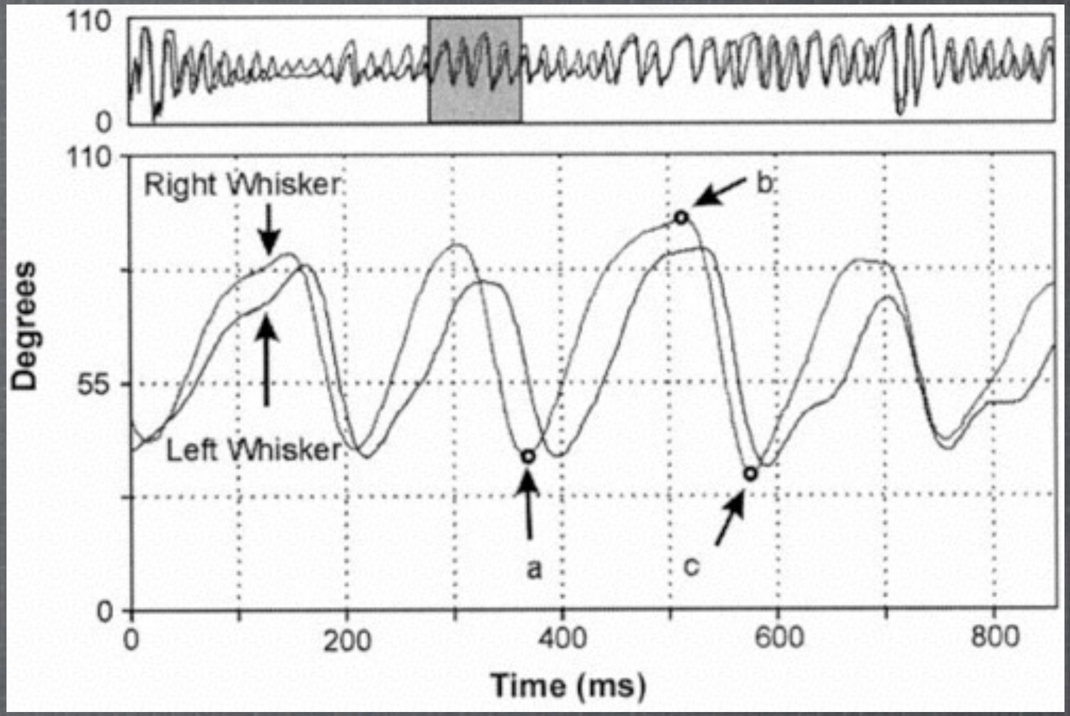
Gao, Bermejo, & Ziegler, 2001

Frequency 5-15hz

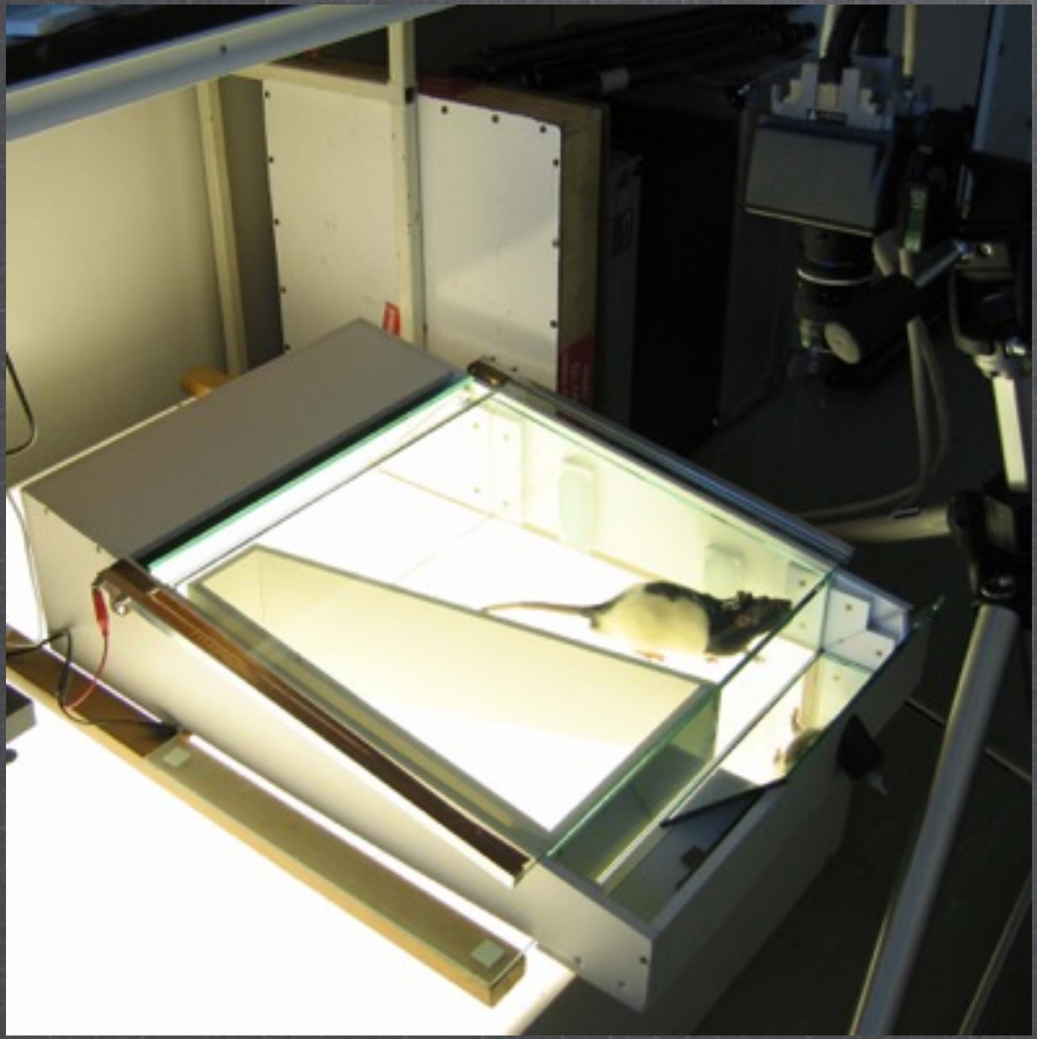
Generally symmetric

Generally synchronous

But…



Courtesy of Society for Neuroscience. License CC BY NC SA. Source: Gao, Puhong, Roberto Bermejo, and H. Philip Zeigler. "Whisker deafferentation and rodent whisking patterns: Behavioral evidence for a central pattern generator." Journal of Neuroscience 21, no. 14 (2001): 5374-5380.



Source: Grant, Robyn A., Anna L. Sperber, and Tony J. Prescott. "The role of orienting in vibrissal touch sensing." (2012).

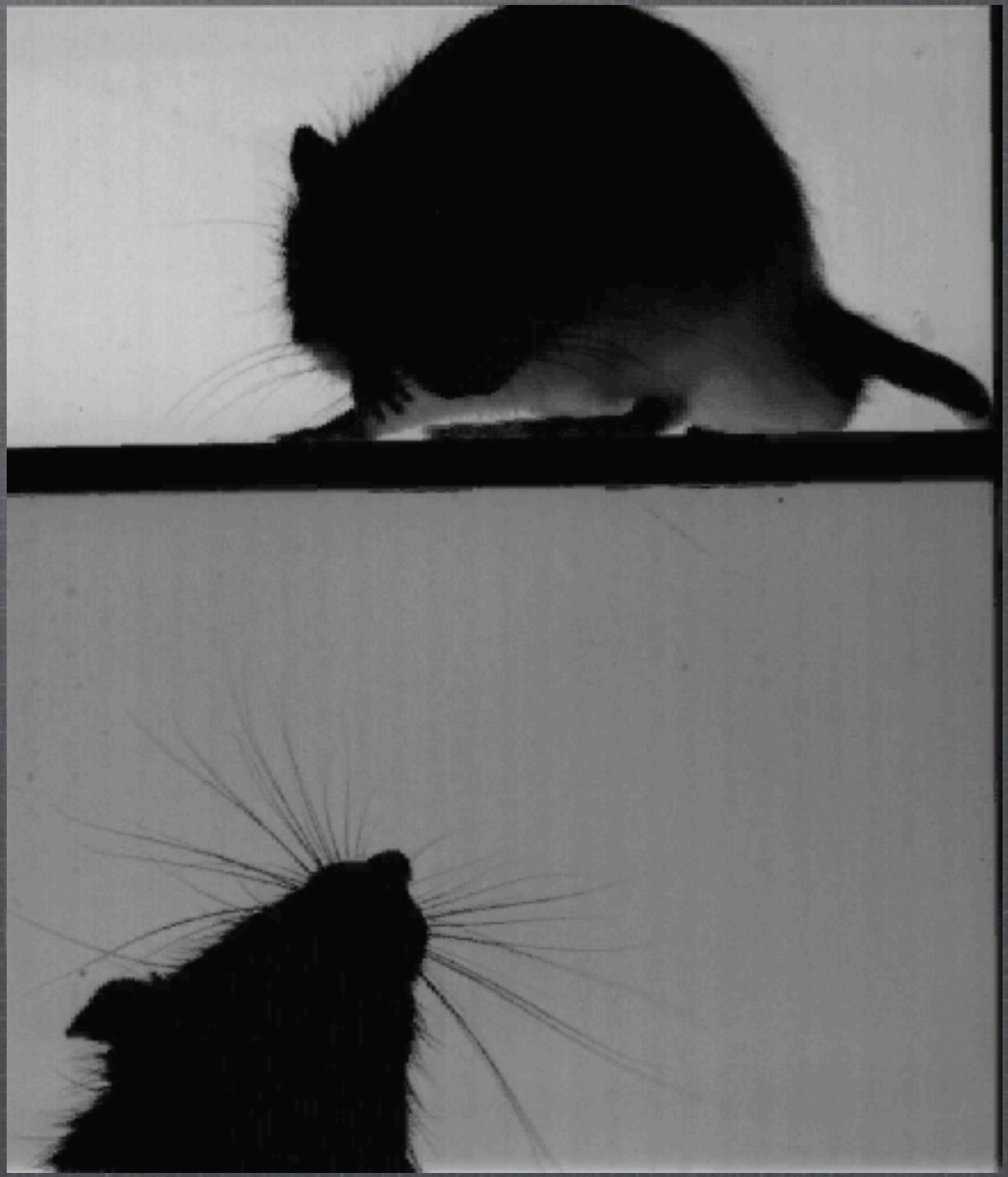
D2:08.08.03.40-400 (3/50x)

EXPLORATORY WHISKING INVOLVES PALPITATING OR 'DABBING'

Viewed from the side—whisking axis is angled downwards

Occurs in phase with head movements such that macro- and micro- vibrissae often contact the floor at the same time

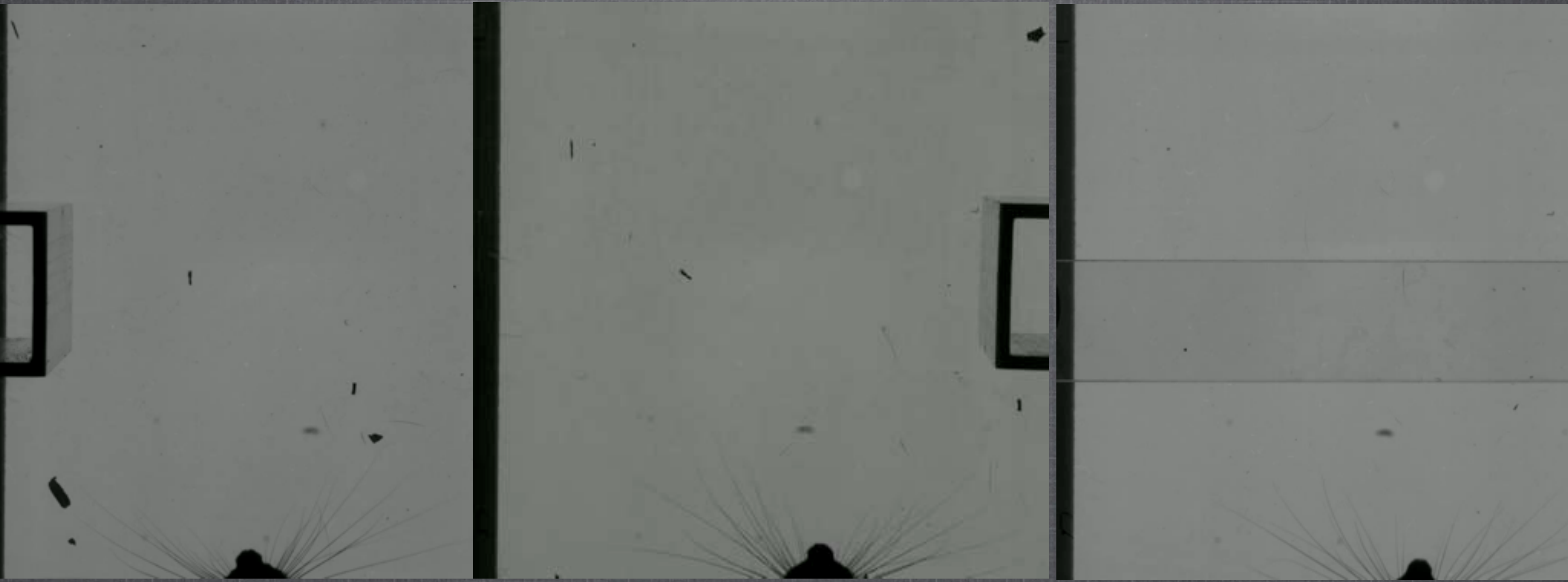
Is directed using head movements at surfaces of interest...



Source: Grant, Robyn A., Anna L. Sperber, and Tony J. Prescott. "The role of orienting in vibrissal touch sensing." (2012).

08.08.03.fl.40–400.15fps.mov

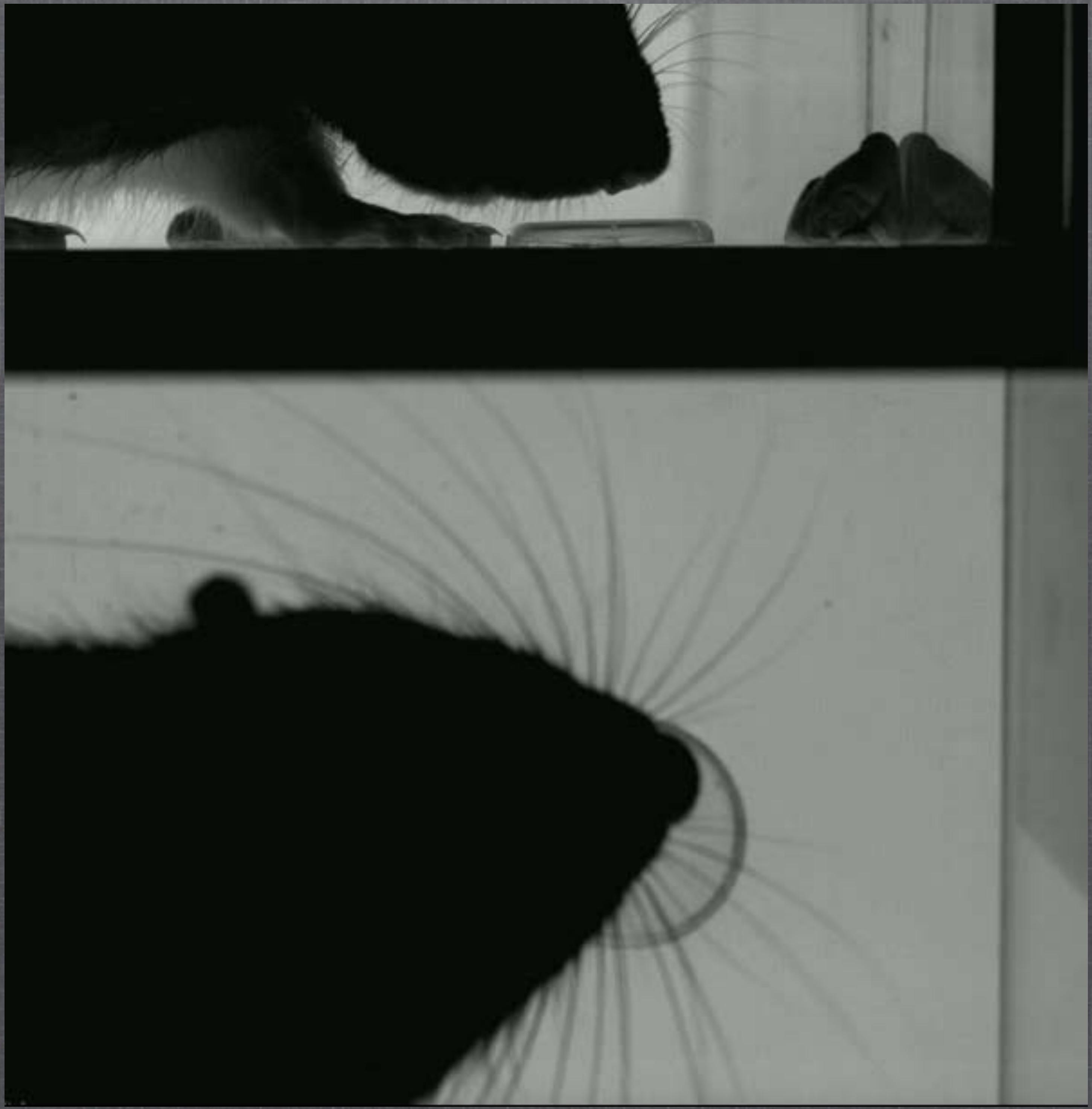
WHISKER CONTACTS ELICIT ATTENTION



Source: Grant, Robyn A., Anna L. Sperber, and Tony J. Prescott. "The role of orienting in vibrissal touch sensing." (2012).

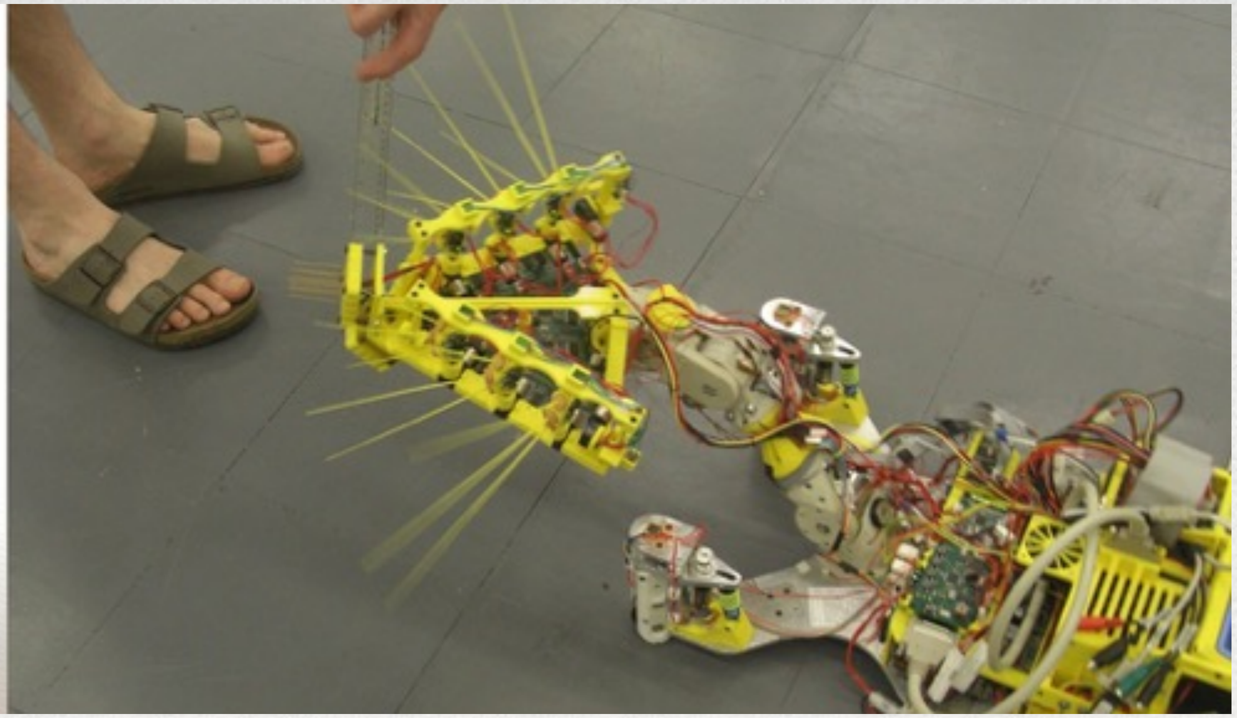
Grant, Sperber & Prescott. 2013. Frontiers in Behavioral Neuroscience.
Arkley, Grant, & Prescott. Submitted.

BY ORIENTING THE RAT BRINGS ITS MICROVIBRISSAE INTO CONTACT WITH SURFACES OF INTEREST

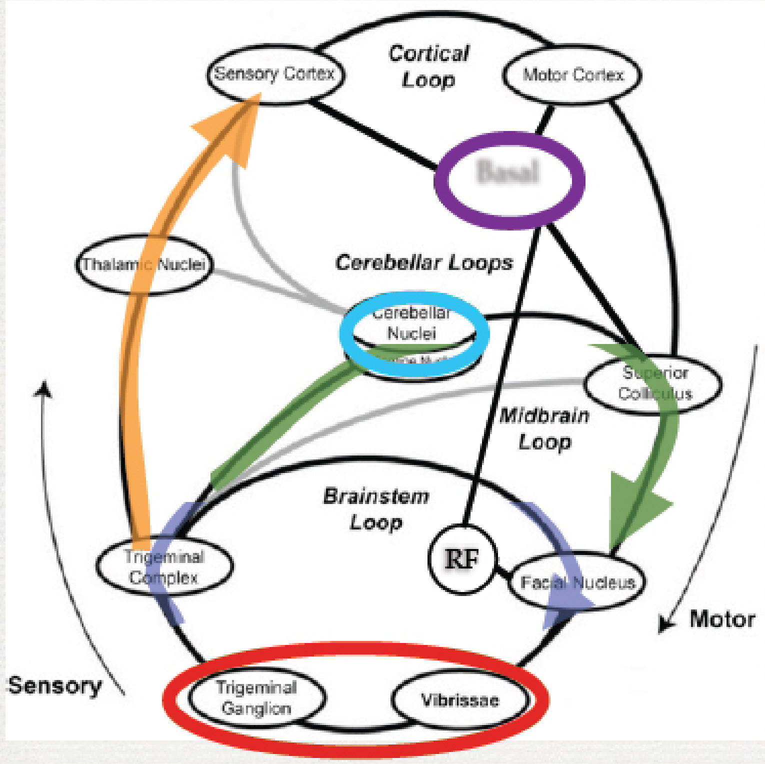


Source: Grant, Robyn A., Anna L. Sperber, and Tony J. Prescott. "The role of orienting in vibrissal touch sensing." (2012).

CONTROL ARCHITECTURE



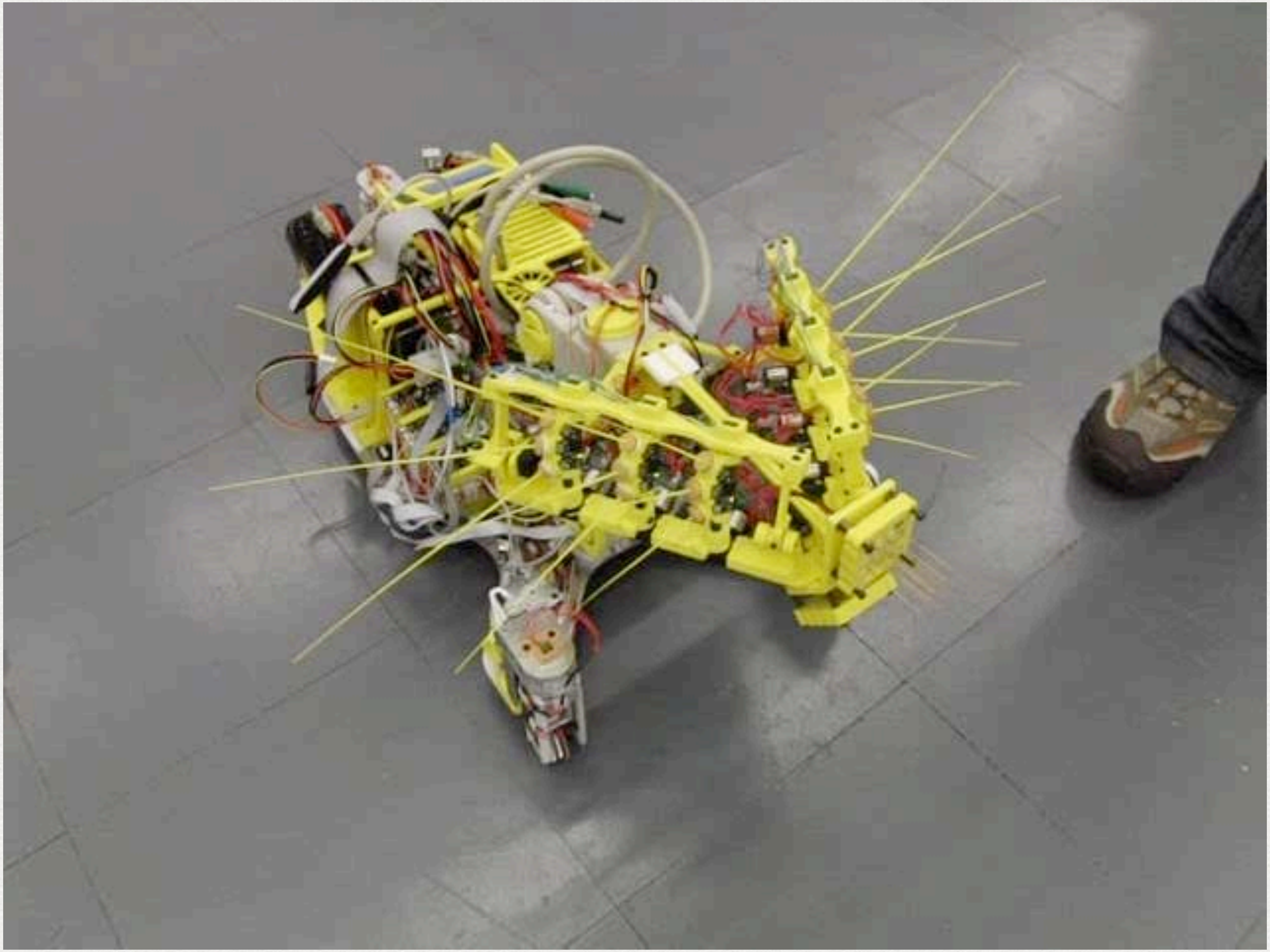
Courtesy of Martin Pearson and Ben Mitchinson. Used with permission.



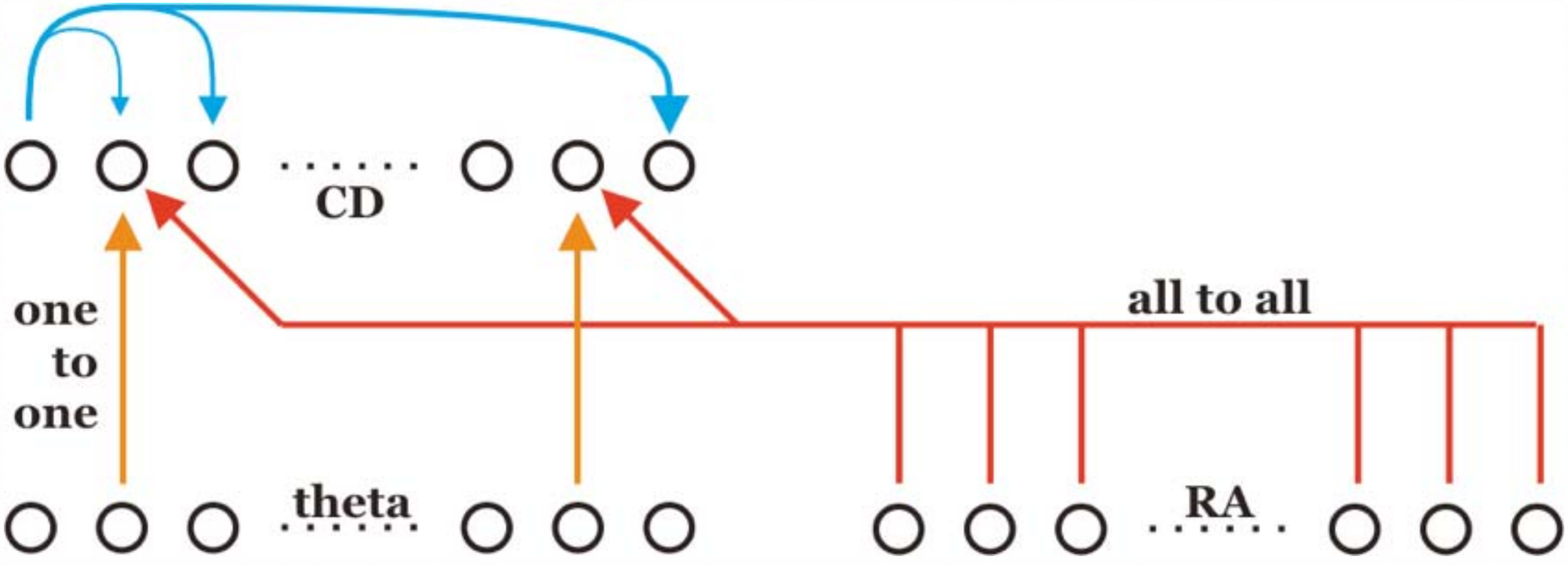
Source: Kleinfeld, David, Ehud Ahissar, and Mathew E. Diamond. "Active sensation:Insights from the rodent vibrissa sensorimotor system."Current opinion in neurobiology 16, no. 4 (2006): 435-444.

Figure removed due to copyright restrictions. Please see the video. Source: Figure 2, Pearson, Martin J., Ben Mitchinson, Jason Welsby, Tony Pipe, and Tony J. Prescott. "Scratchbot: Active tactile sensing in a whiskered mobile robot." In International Conference on Simulation of Adaptive Behavior, pp. 93-103. Springer Berlin Heidelberg, 2010.

WHISKER-GUIDED ORIENTING IN SCRATCHBOT



ACCURATE ORIENTING REQUIRES A TRANSFORM FROM WHISKER-CENTRIC TO HEAD-CENTRIC CO-ORDINATES



- Coincidence detector requires input from two model cell populations encoding deflection (RA) and whisker angle (theta)

- CD cells have been identified in subgranular layers of S1 cortex (Curtis & Kleinfeld, *Nature Neuroscience*, 2009)

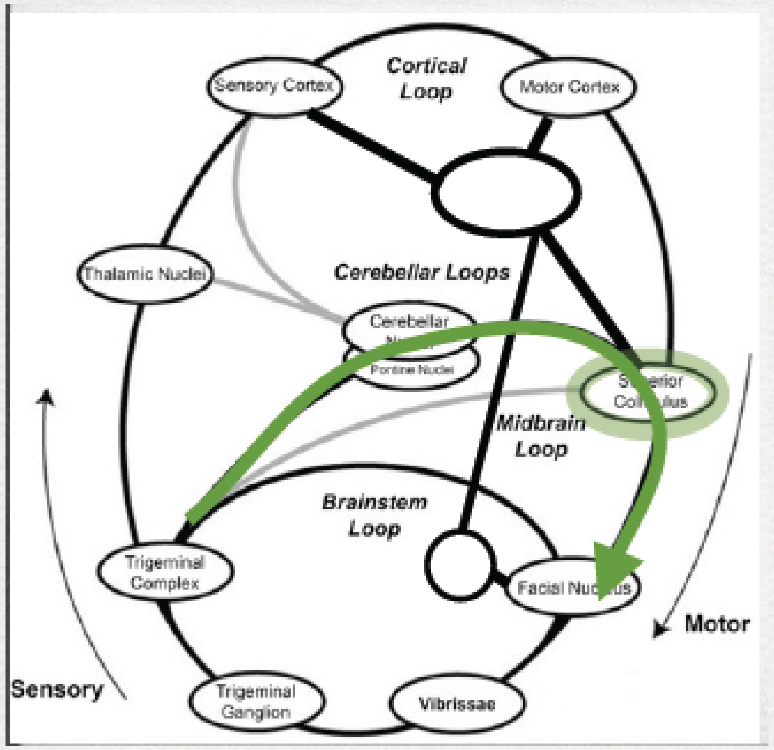
A MODEL OF THE SUPERIOR COLLICULUS PROVIDES THE REQUIRED HEAD-CENTERED MAP

SC vibrissal-sensitive neurons have broadly tuned receptive fields that overlap the head-centered visual map.

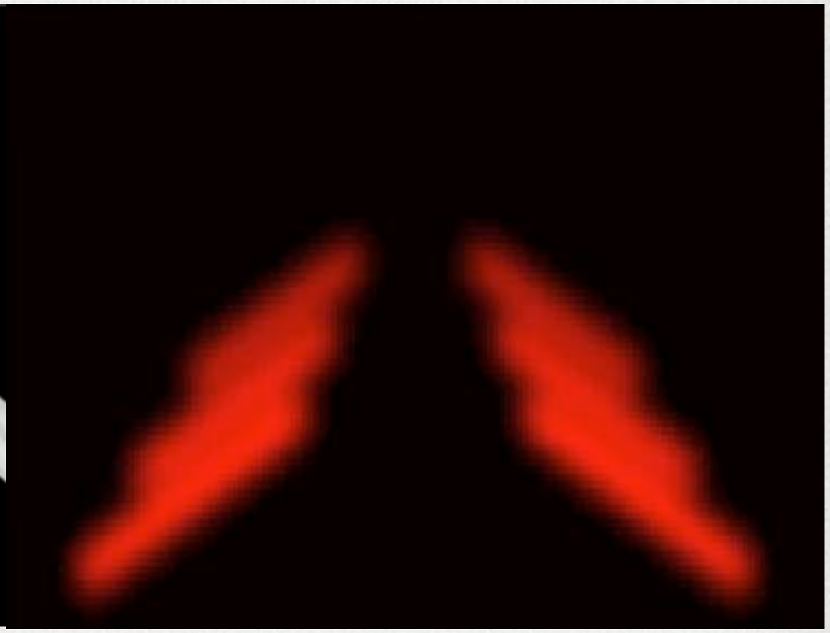
Cells in the intermediate layers of SC respond rapidly to both single whisker and multi-whisker input (e.g. Cohen et al. 2008).

Image removed due to copyright restrictions.
Please see the video.
Source: Drager, Ursula C., and D. H. Hubel. "Topography of visual and somatosensory projections to mouse superior colliculus." Journal of Neurophysiology 39, no. 1 (1976): 91-101.

Figure (right) from Drager and Hubel, 1976

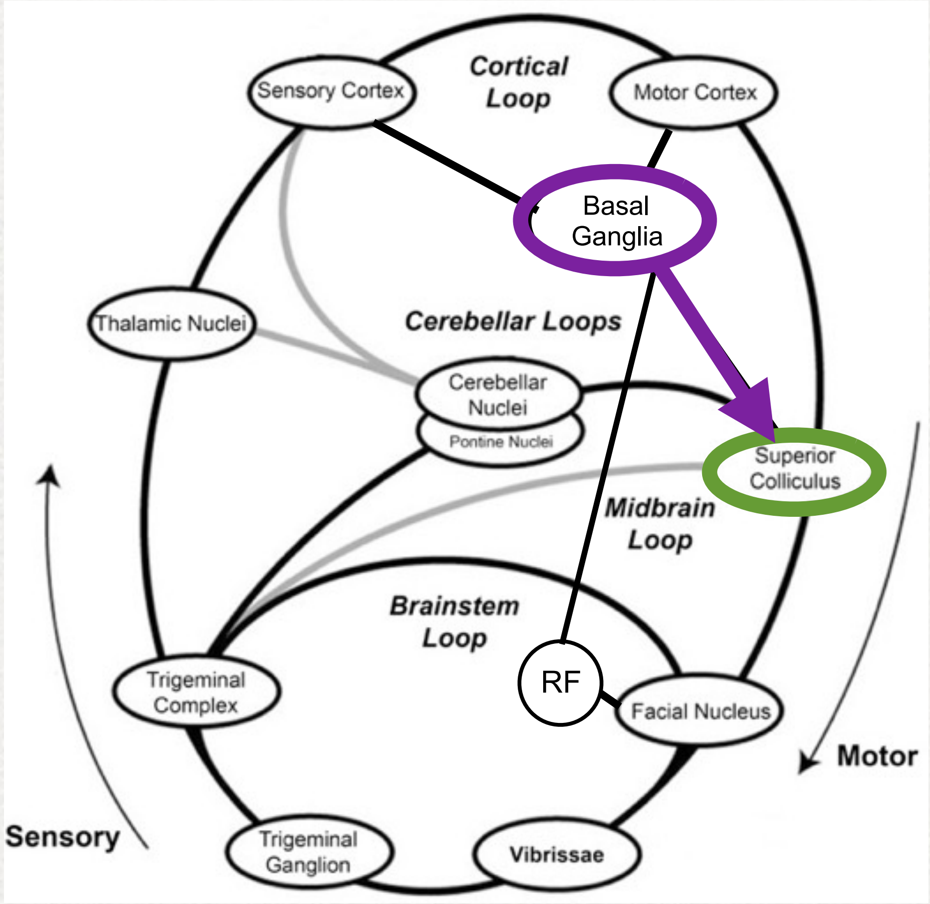


Source: Kleinfeld, David, Ehud Ahissar, and Mathew E. Diamond. "Active sensation: Insights from the rodent vibrissa sensorimotor system." Current opinion in neurobiology 16, no. 4 (2006): 435-444.



A MODEL OF THE BASAL GANGLIA ACTS TO GATE REQUESTS FOR ORIENTING

The animal/robot needs to **decide** whether or not to orient to a given stimulus, and, when there are multiple peaks in the collicular map which peak to select. **Basal ganglia** inhibitory output to colliculus prevent unwanted orienting movements



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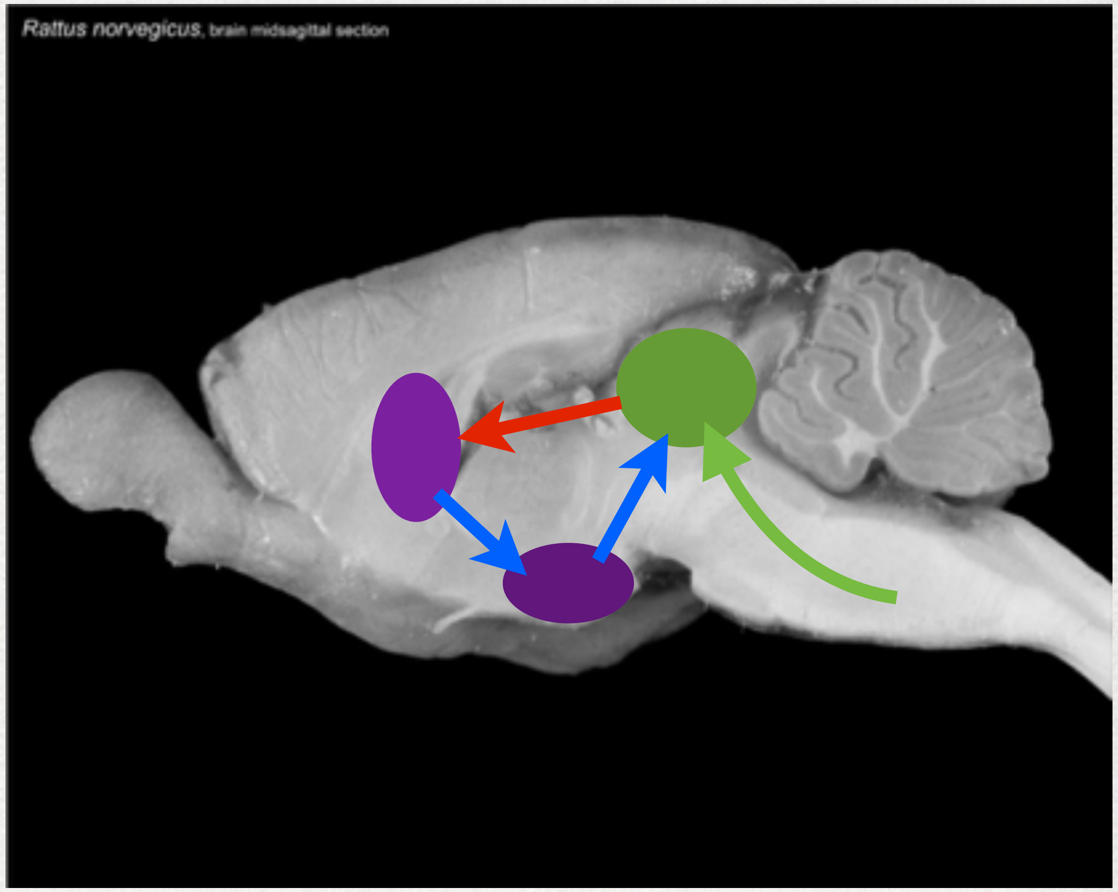
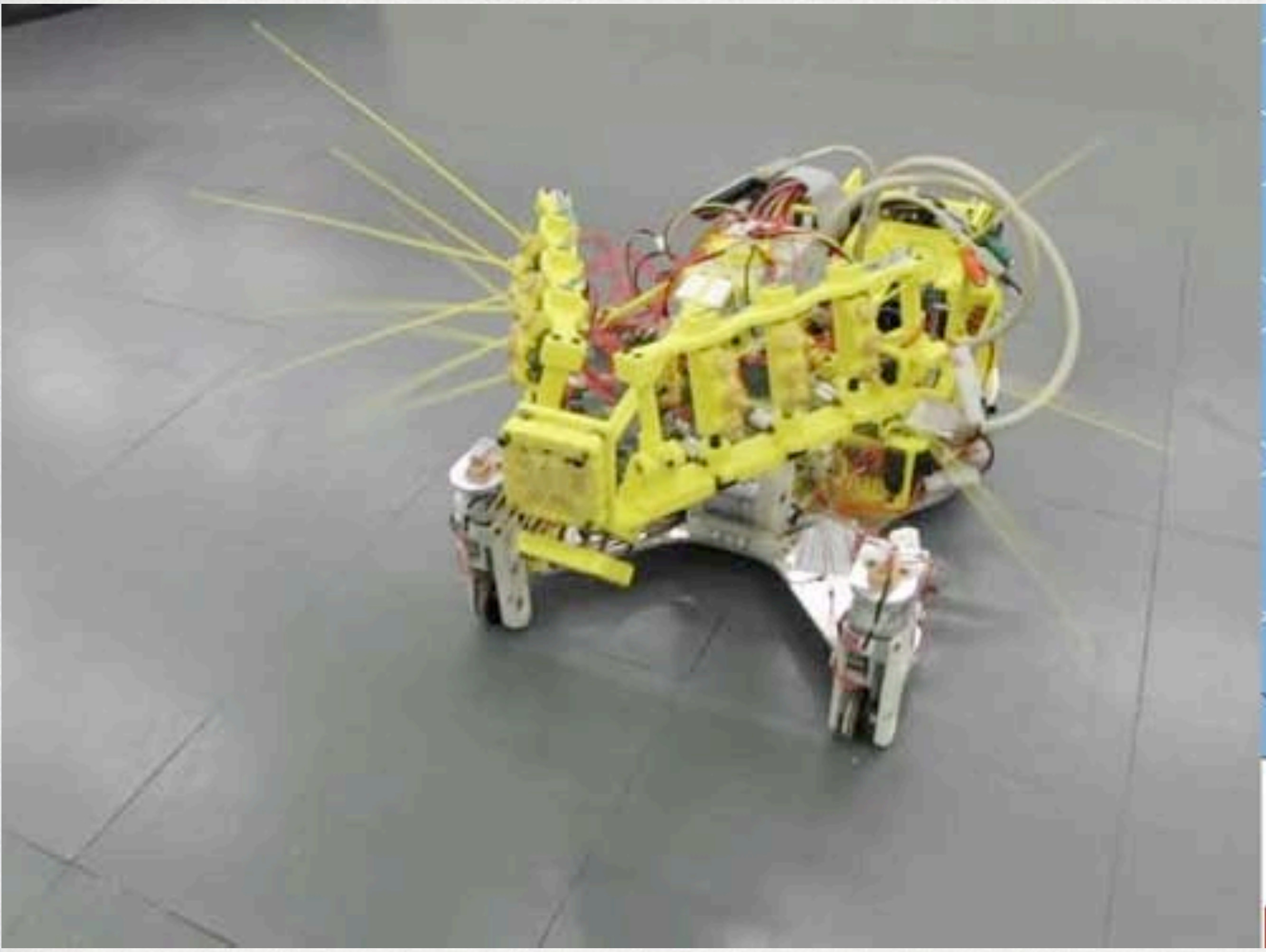
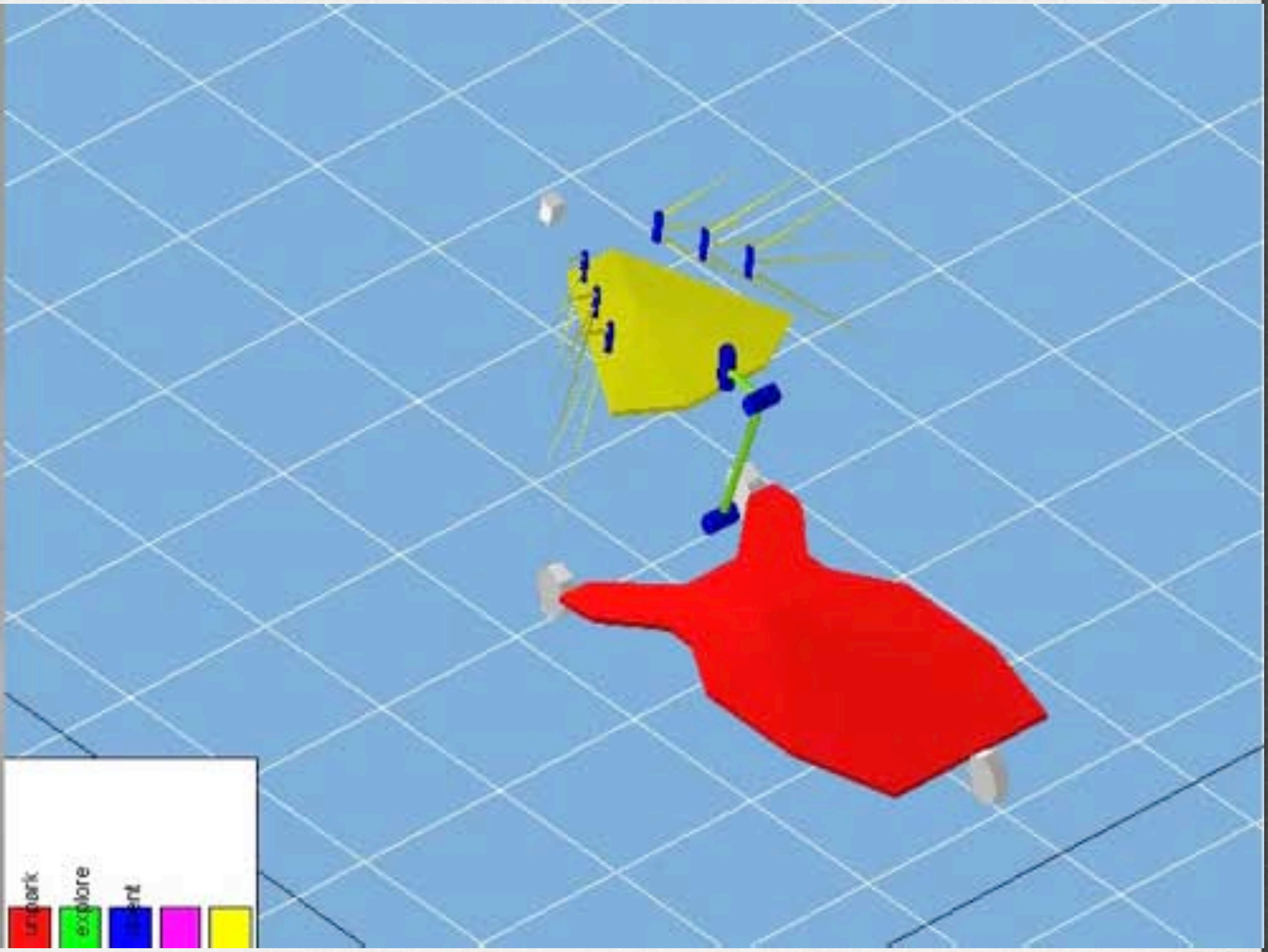


ACTION SELECTION USING A MODEL OF THE BASAL GANGLIA





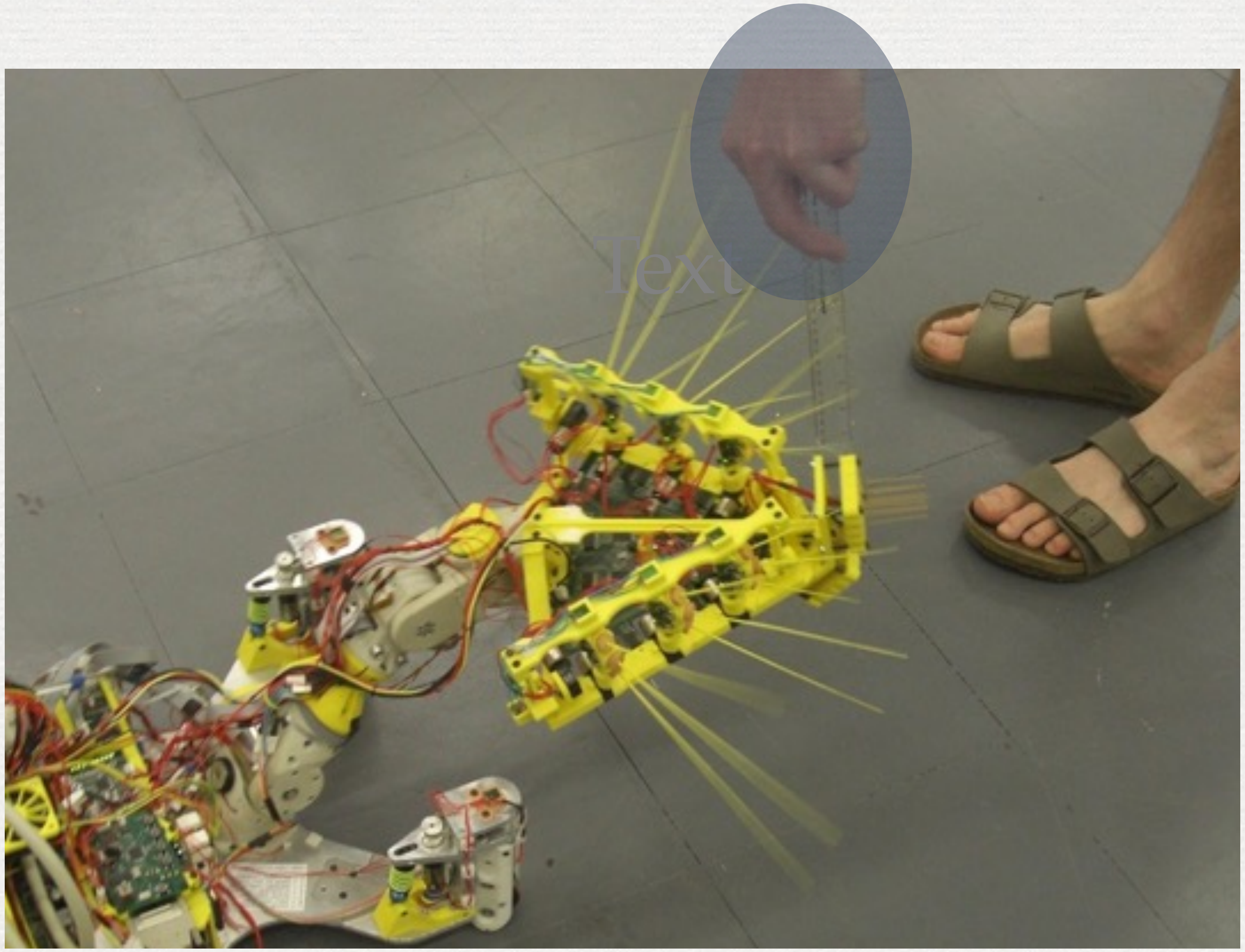
The selected channel is activated by the removal of inhibition

Prescott et al. 2006.*Neural Networks,* 19(1):31-61.
Pearson et al. 2010. *11th International Conference on Simulation of Adaptive Behavior.*

NOT YET A COMPLETE THEORY...

The task is harder than it looks due to sensory noise induced by self-motion that can lead to ***ghost orients***

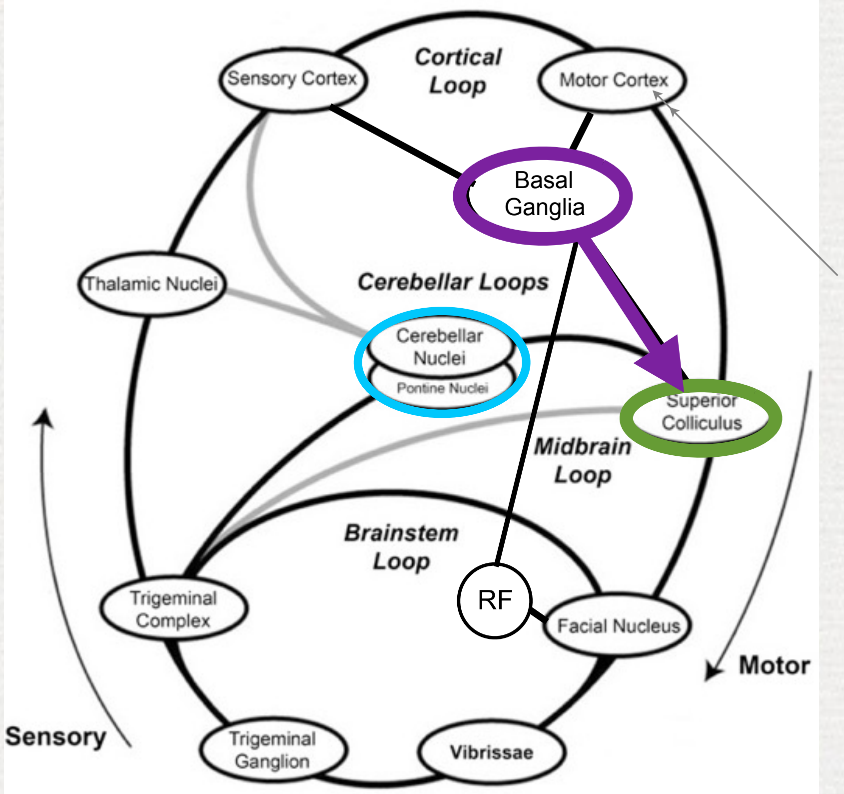
Real or not?



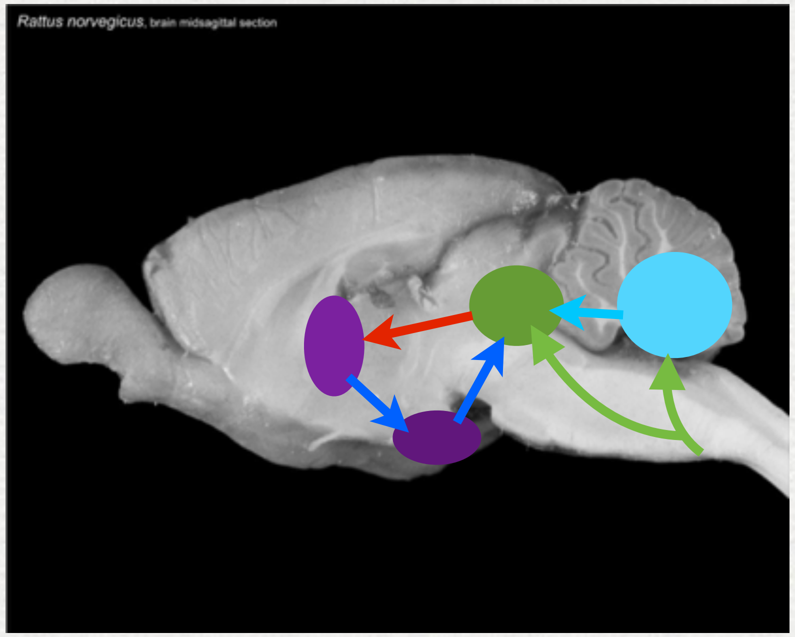
Courtesy of Martin Pearson and Ben Mitchinson. Used with permission.

A MODEL OF THE CEREBELLUM FILTERS SENSORY NOISE DUE TO SELF-MOVEMENT

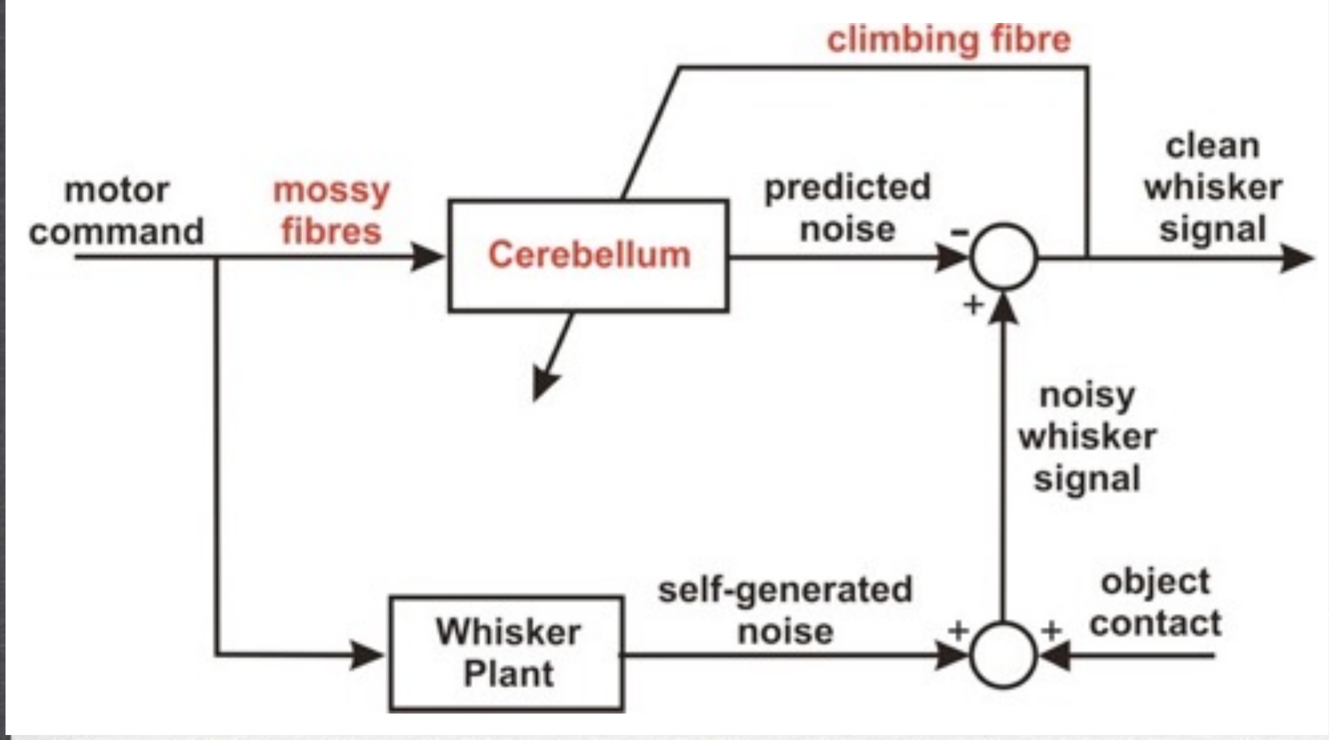
Cerebellum implicated in cancelling tickle sensation in humans (Blakemore et al. 1998, Nat. Neuros). Pre-cerebellar structures cancel self-generated noise in electric fish (Bell et al. 2008, Ann. Rev. Neurosci.)

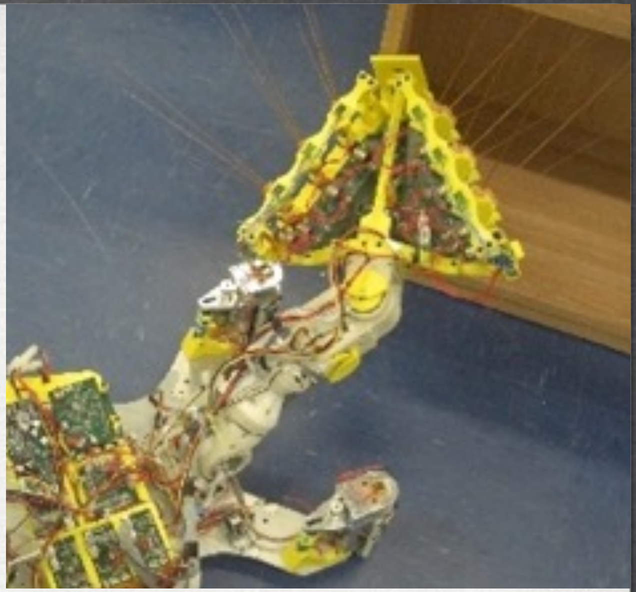


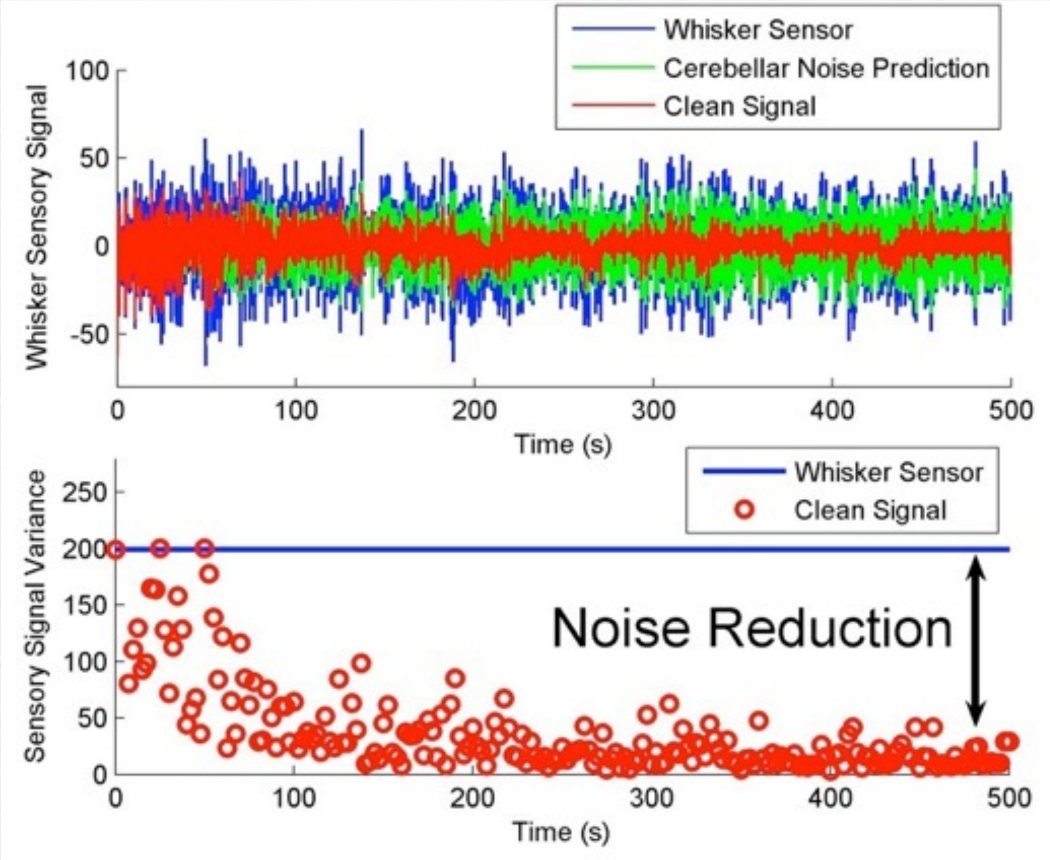
Source: Kleinfeld, David, Ehud Ahissar, and Mathew E. Diamond. "Active sensation: Insights from the rodent vibrissa sensorimotor system." Current opinion in neurobiology 16, no. 4 (2006): 435-444.



CEREBELLAR FILTERING







An adaptive filter scheme modelled on the cerebellum can predict contact signals due to self-movement.

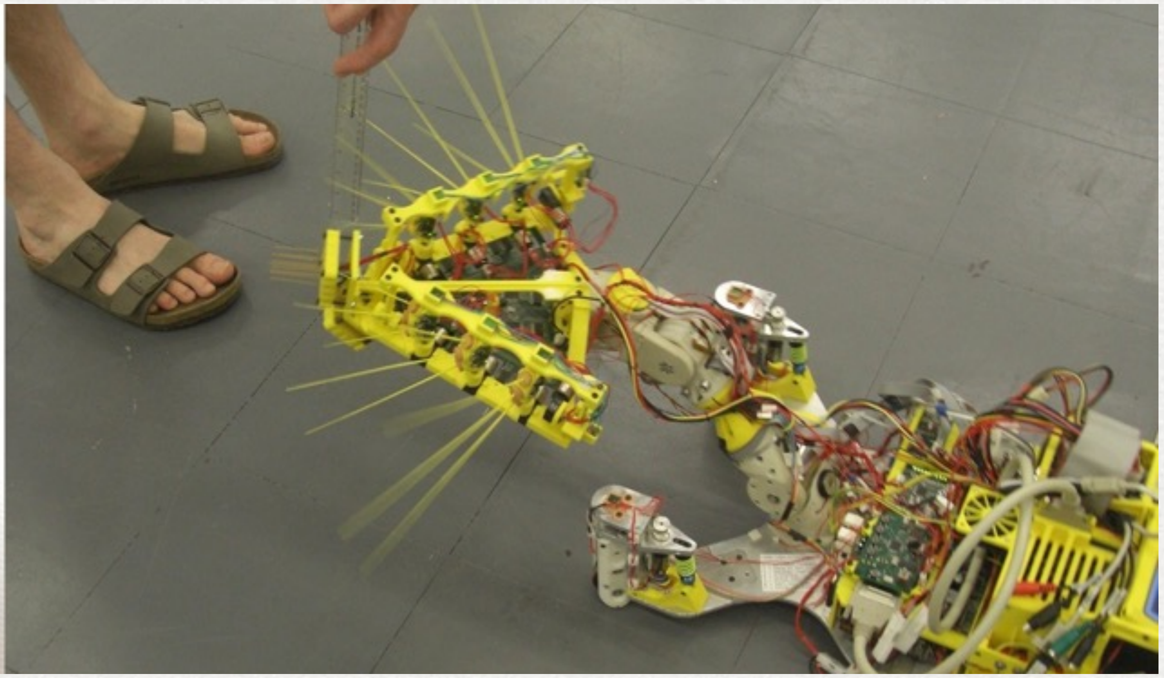
The input to the system is the motor command to the whiskers.

The training signal is the cleaned-up whisker contact signal.

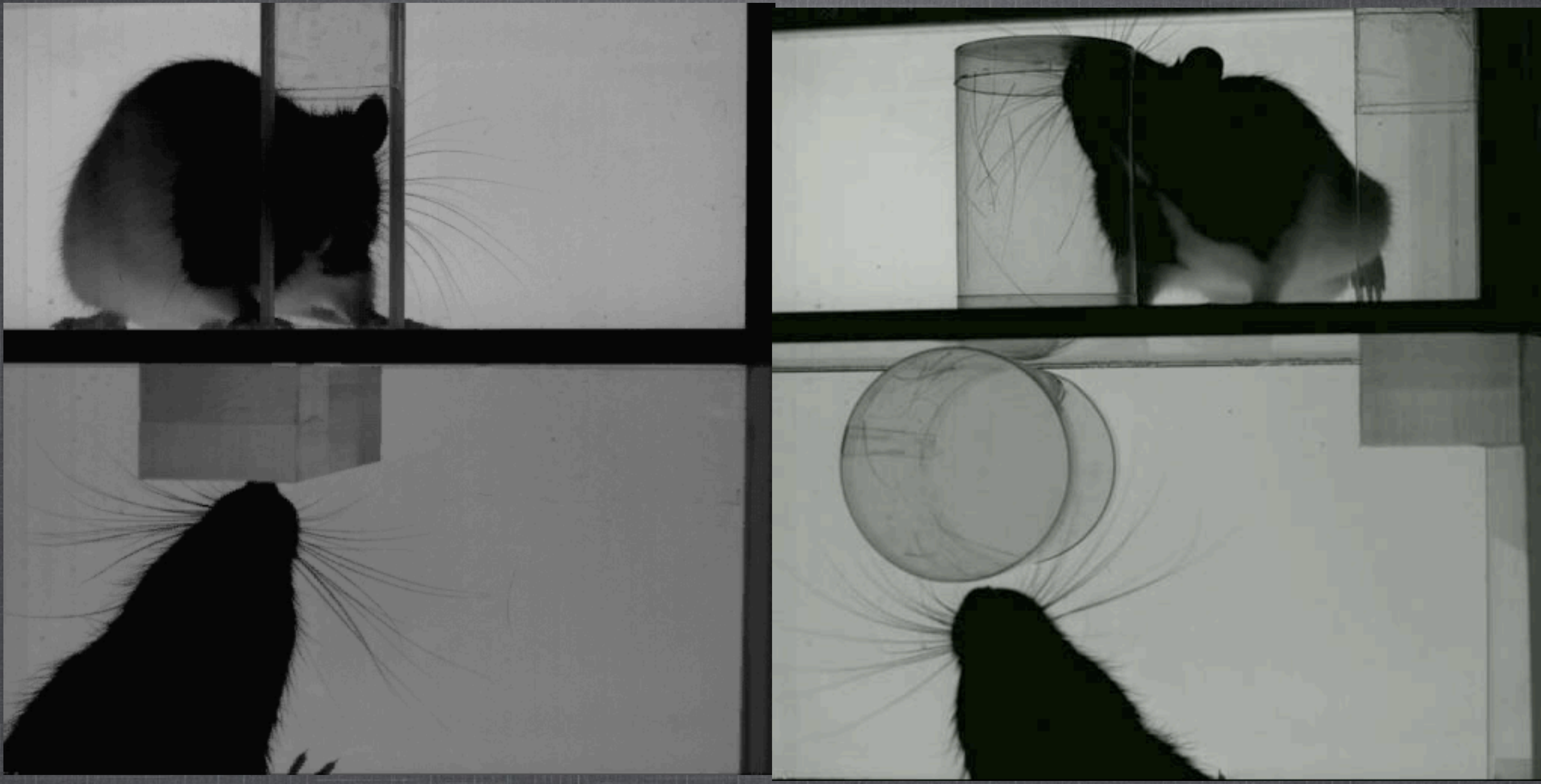
Source: Anderson, Sean R., Martin J. Pearson, Anthony Pipe, Tony Prescott, Paul Dean, and John Porrill. "Adaptive cancelation of self-generated sensory signals in a whisking robot." IEEE Transactions on Robotics 26, no. 6 (2010): 1065-1076.

Anderson et al. IEEE Transactions in Robotics, 2011

WE NOW HAVE A SYSTEMS-LEVEL MODEL OF ORIENTING, BUT WHAT ABOUT FINE CONTROL OF VIBRISSAE?



Courtesy of Martin Pearson and Ben Mitchinson. Used with permission.



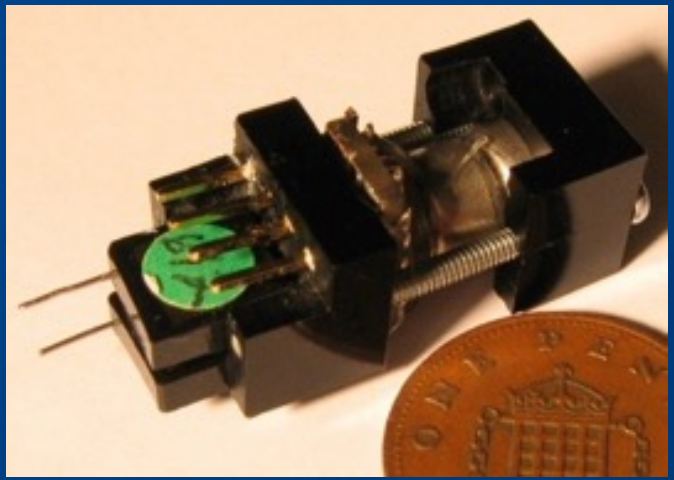
Source: Grant, Robyn A., Anna L. Sperber, and Tony J. Prescott. "The role of orienting in vibrissal touch sensing." (2012).

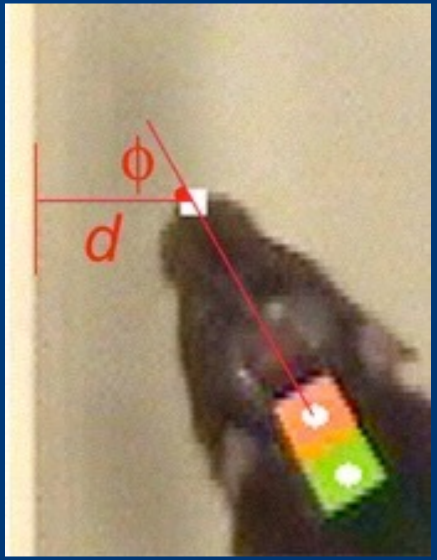
DURING UNCONSTRAINED EXPLORATION WHISKER MOVEMENT CAN BECOME STRONGLY ASYMMETRIC WITH CHANGES IN WHISKER SPREAD

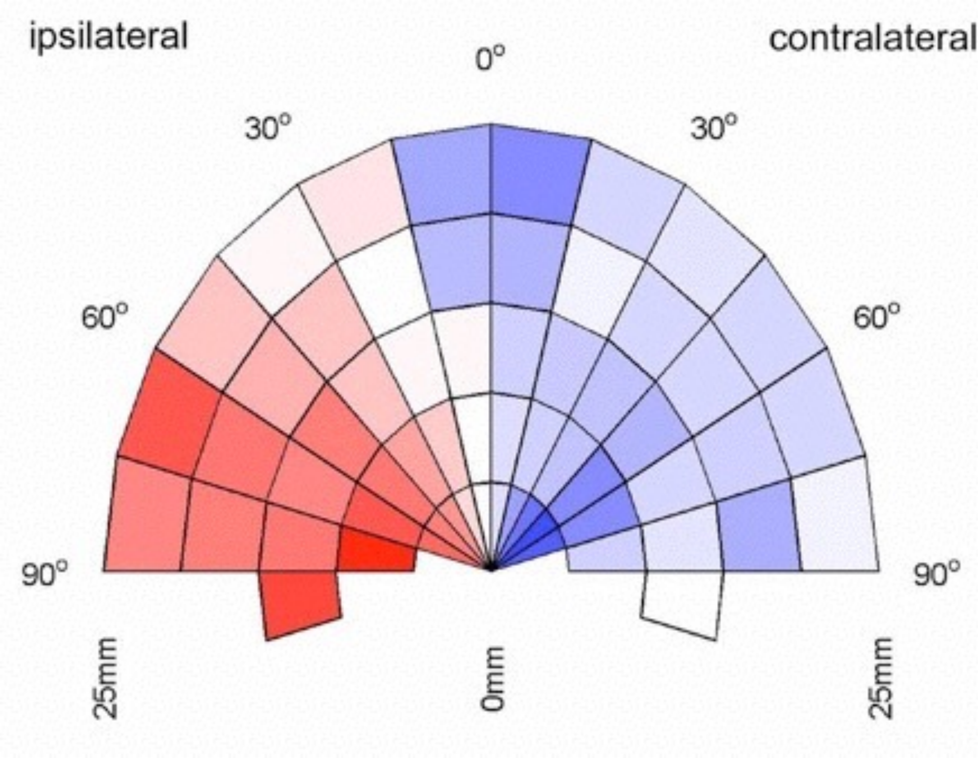
Mitchinson, Martin, Grant, Prescott, 2007. Proceedings of the Royal Society B.

Recorded over extended periods

Mitchinson, Martin, Grant, Prescott, Proc. Roy Soc. B. 2007

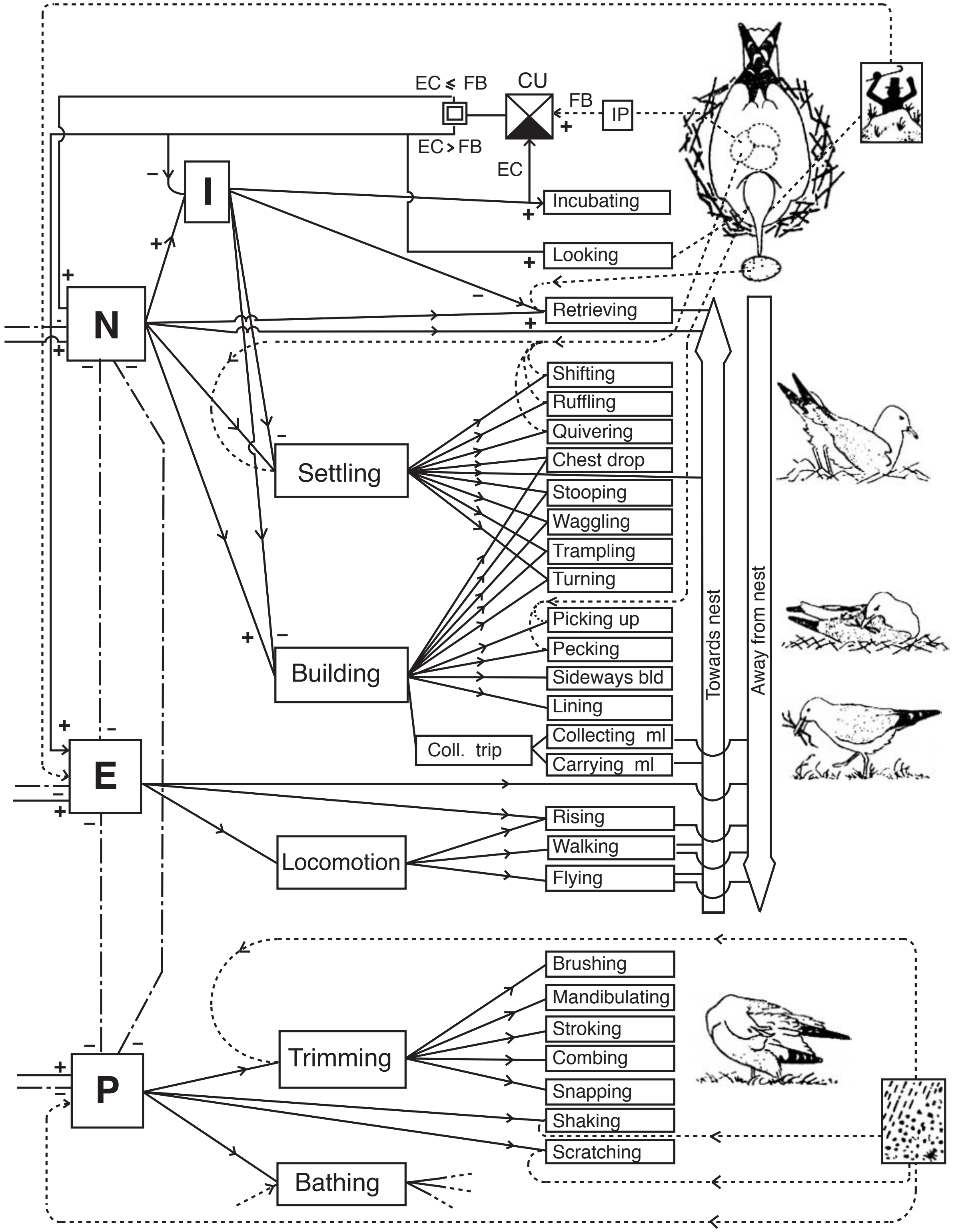






Source: Mitchinson, Ben, Chris J. Martin, Robyn A. Grant, and Tony J. Prescott. "Feedback control in active sensing: Rat exploratory whisking is modulated by environmental contact." Proceedings of the Royal Society of London B: Biological Sciences 274, no. 1613 (2007): 1035-1041.

How do we decompose control?



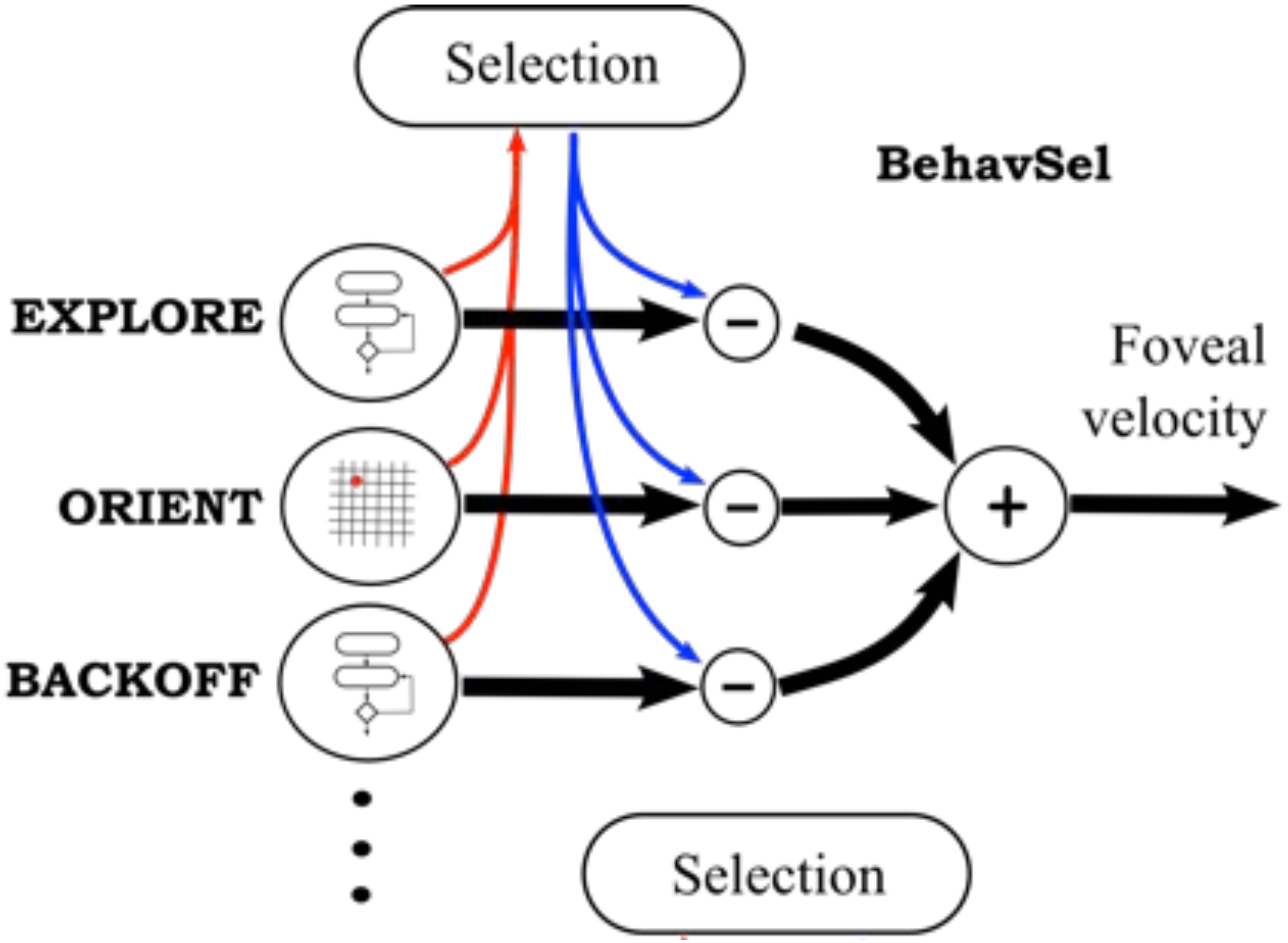
Model of behavior systems in the herring gull from Baerends (1970).

The right-hand column shows the elementary behaviors or "fixed action patterns". To the left of these are the superimposed first and second order control systems (N= nesting system, E= escape system, P= preening system).

The main behaviour systems mutually inhibit one another.

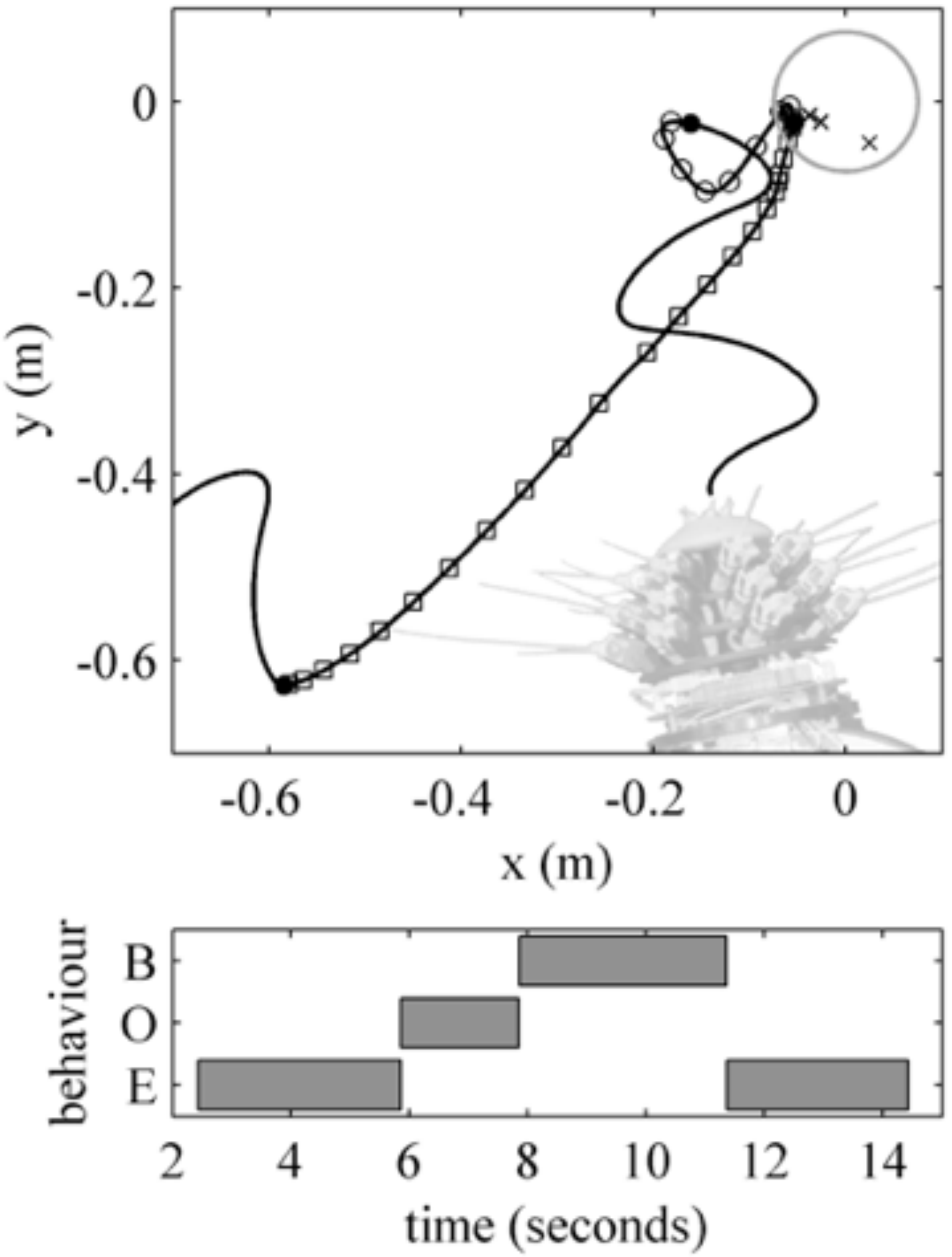
Source: Baerends, Gerard P. "A model of the functional organization of incubation behaviour." Behaviour. Supplement (1970): 263-312.

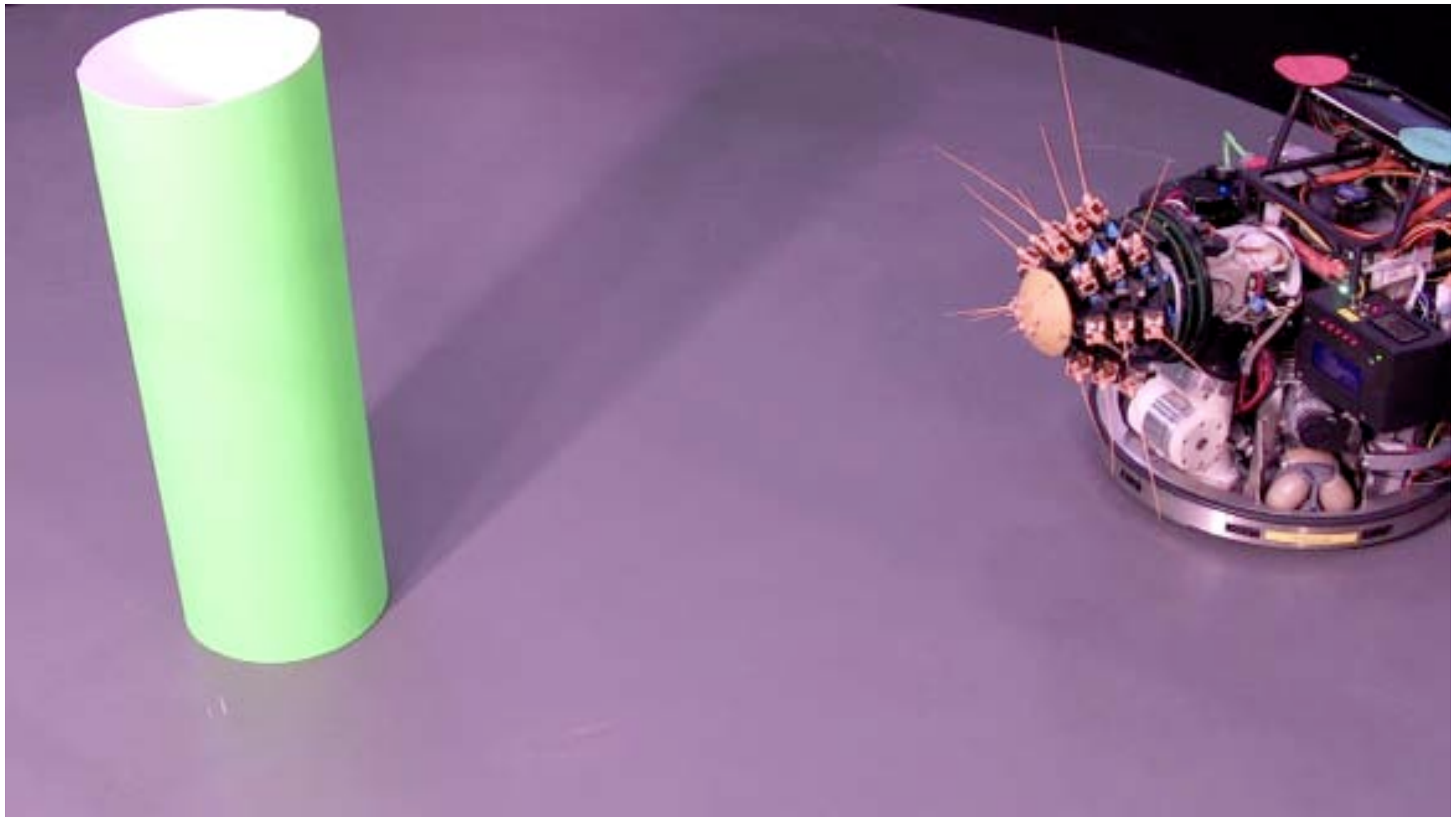
Behavioural Decomposition



Source: Mitchinson, Ben, Martin J. Pearson, Anthony G. Pipe, and Tony J. Prescott. "The emergence of action sequences from spatial attention: Insight from rodent-like robots." In Conference on Biomimetic and Biohybrid Systems, pp. 168-179. Springer Berlin Heidelberg, 2012.

Fixed action patterns

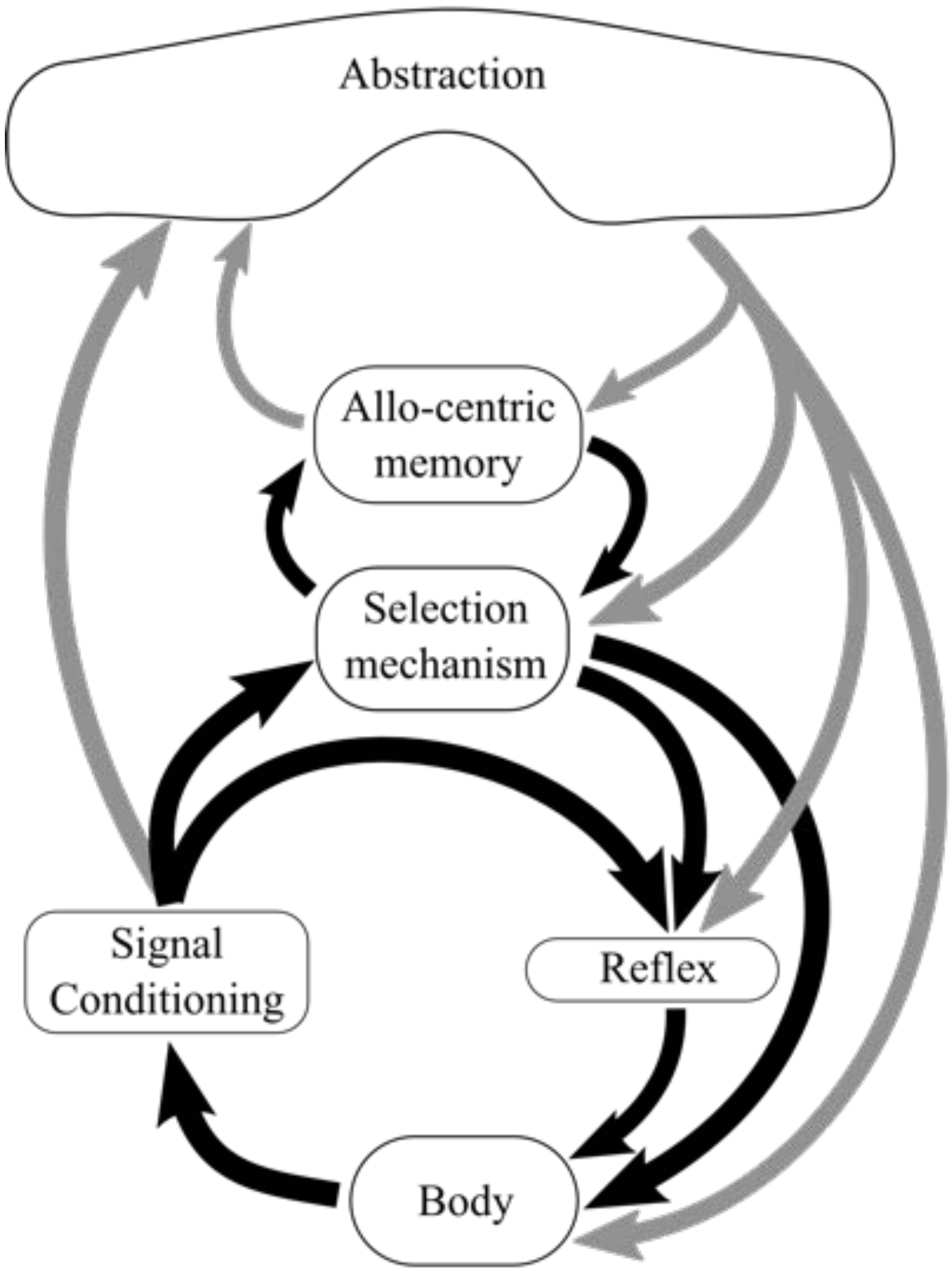


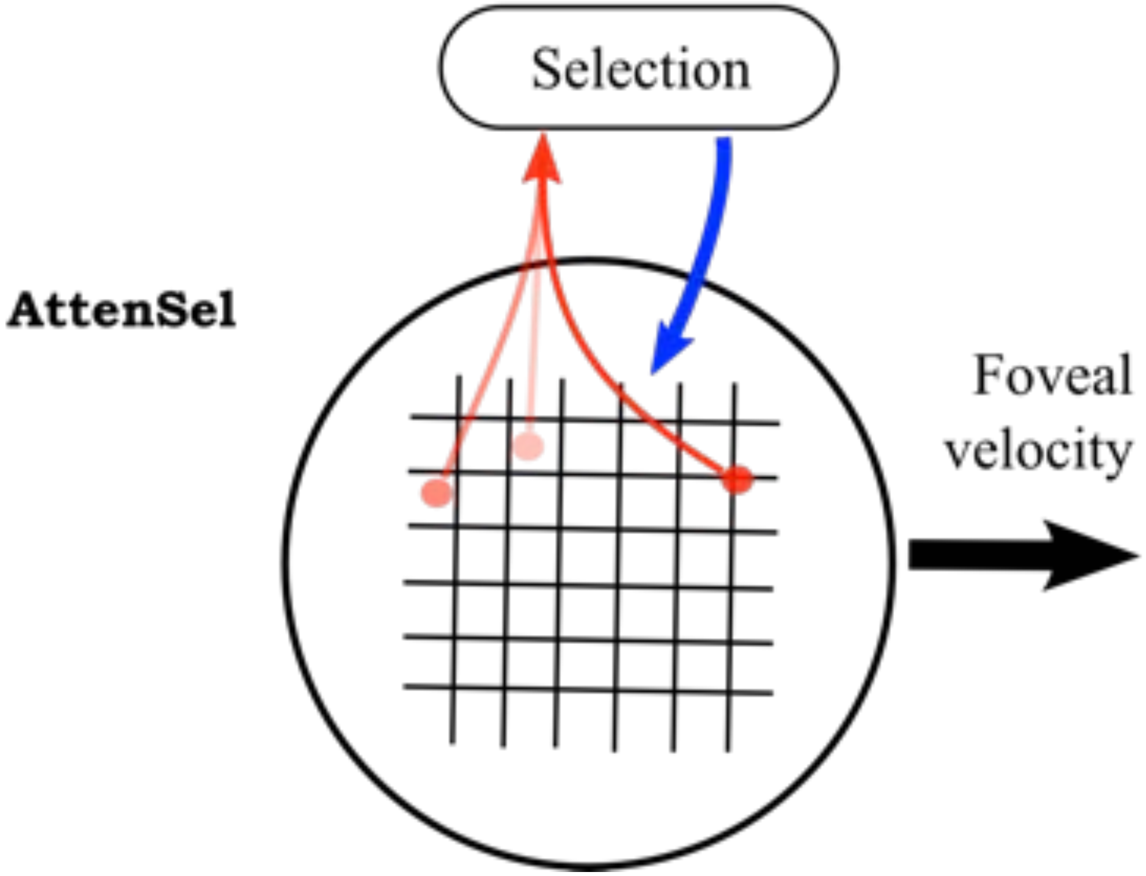


Ethogram generated from the control system

Source: Mitchinson, Ben, Martin J. Pearson, Anthony G. Pipe, and Tony J. Prescott. "The emergence of action sequences from spatial attention: Insight from rodent-like robots." In Conference on Biomimetic and Biohybrid Systems, pp. 168-179. Springer Berlin Heidelberg, 2012.

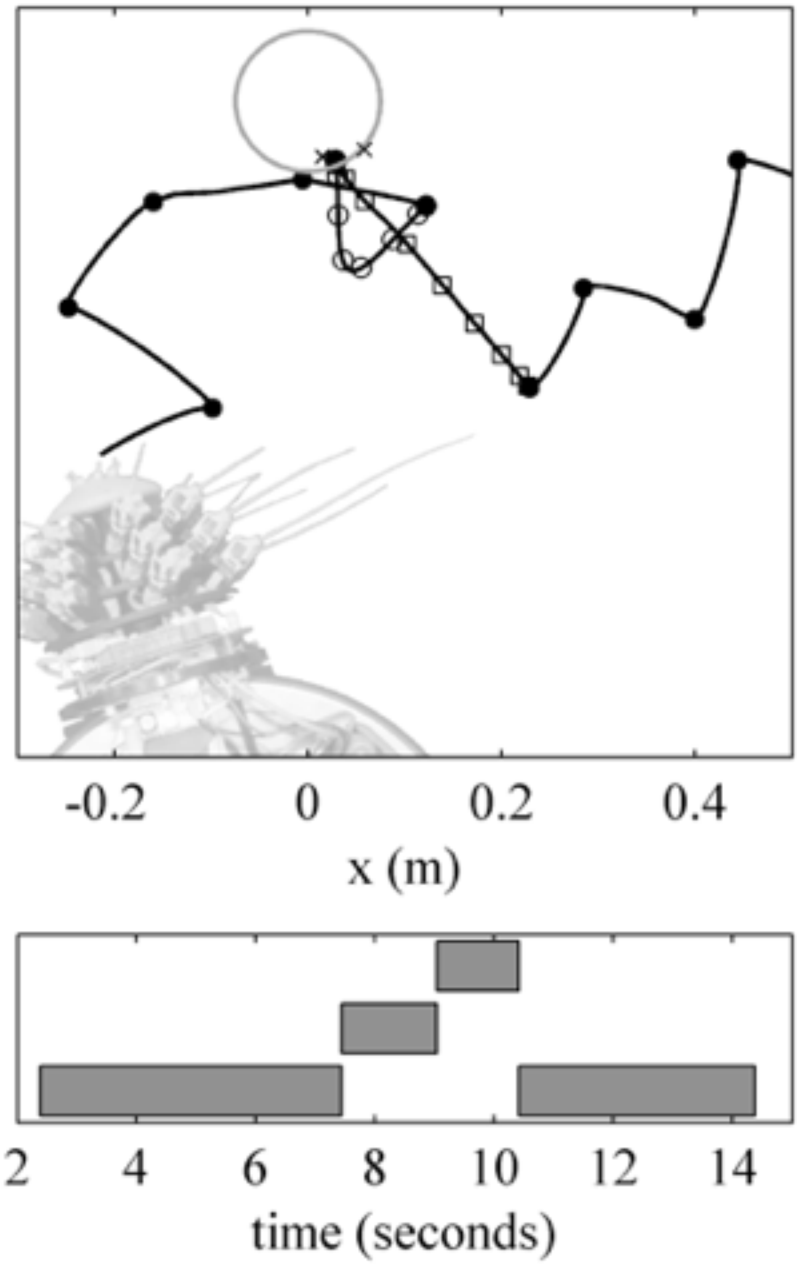
Spatial Attention Mechanism

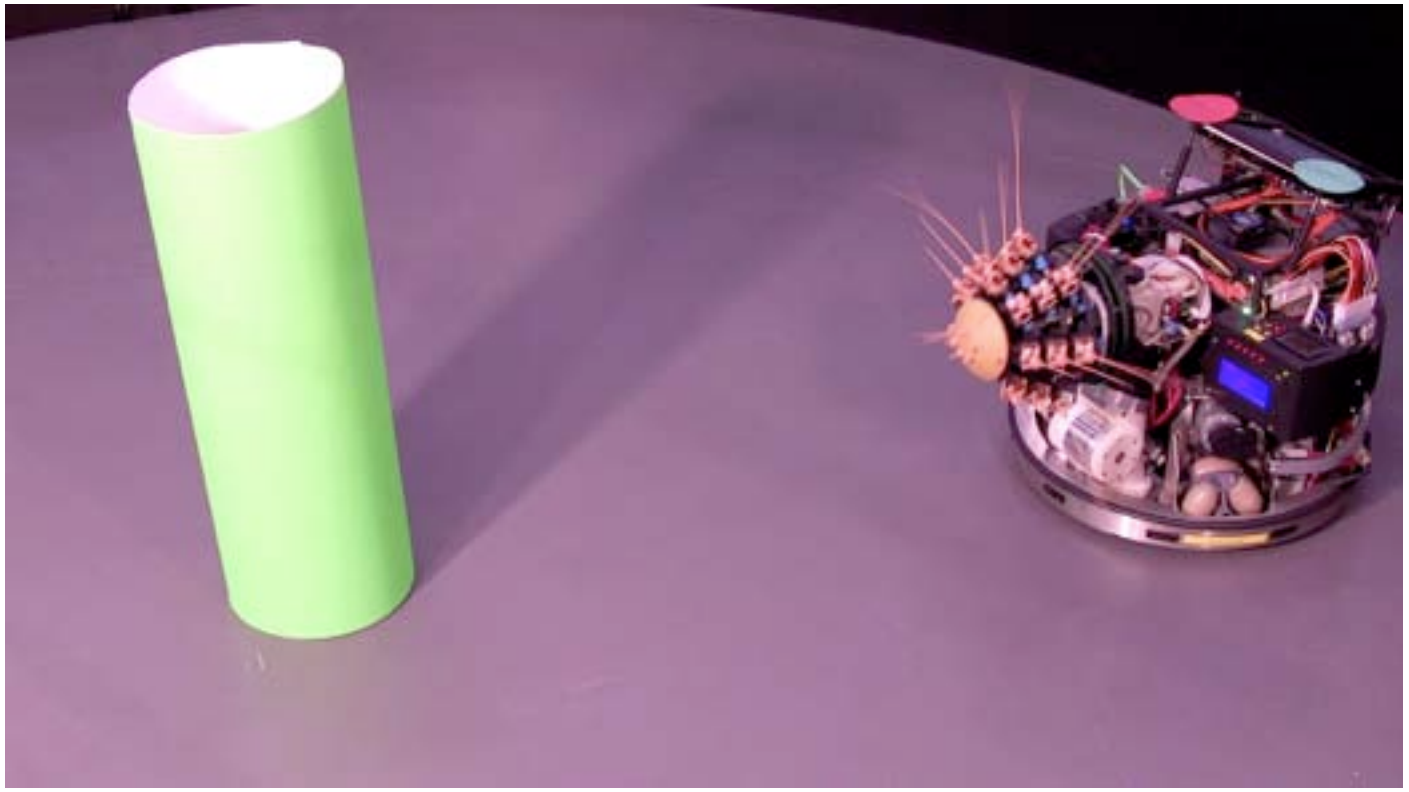




Source: Mitchinson, Ben, Martin J. Pearson, Anthony G. Pipe, and Tony J. Prescott. "The emergence of action sequences from spatial attention: Insight from rodent-like robots." In Conference on Biomimetic and Biohybrid Systems, pp. 168-179. Springer Berlin Heidelberg, 2012.

Spatial Attention Model





Ethogram generated by video coding
Action selection is a consequence of spatial salience

Source: Mitchinson, Ben, Martin J. Pearson, Anthony G. Pipe, and Tony J. Prescott. "The emergence of action sequences from spatial attention: Insight from rodent-like robots." In Conference on Biomimetic and Biohybrid Systems, pp. 168-179. Springer Berlin Heidelberg, 2012.

HUMAN SACCADIC EYE-MOVEMENTS REVEAL SPATIAL ATTENTION

Eye movement reflects the human thought processes; so the observer's thought may be followed to some extent from records of eye movement (the thought accompanying the examination of the particular object).

It is easy to determine from these records which elements attract the observer's eye (and, consequently, his thought), in what order, and how often"

Albert Yarbus, *Eye Movements and Vision*,1967


Ilya Repin, The Unexpected Visitor, 1884

This painting by Ilya Repin is in the public domain.

SALIENCE MAPS FOR VISUAL ATTENTION

Figure showing primate visual attention removed due to copyright restrictions. Please see the video.

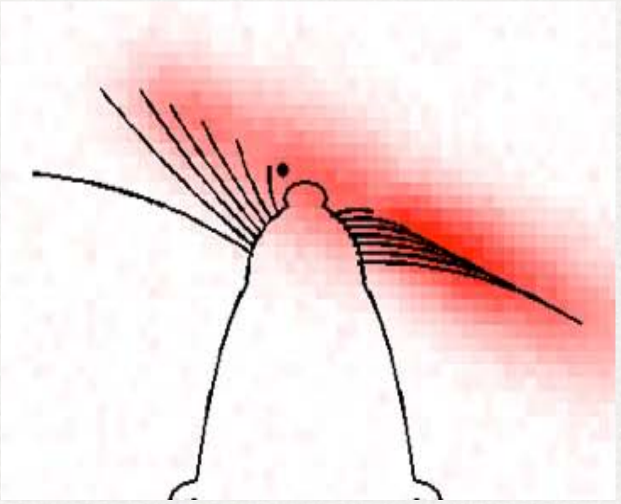
(Itti, 2001; Elmer et al., 2001; Berger et al. 2005.)

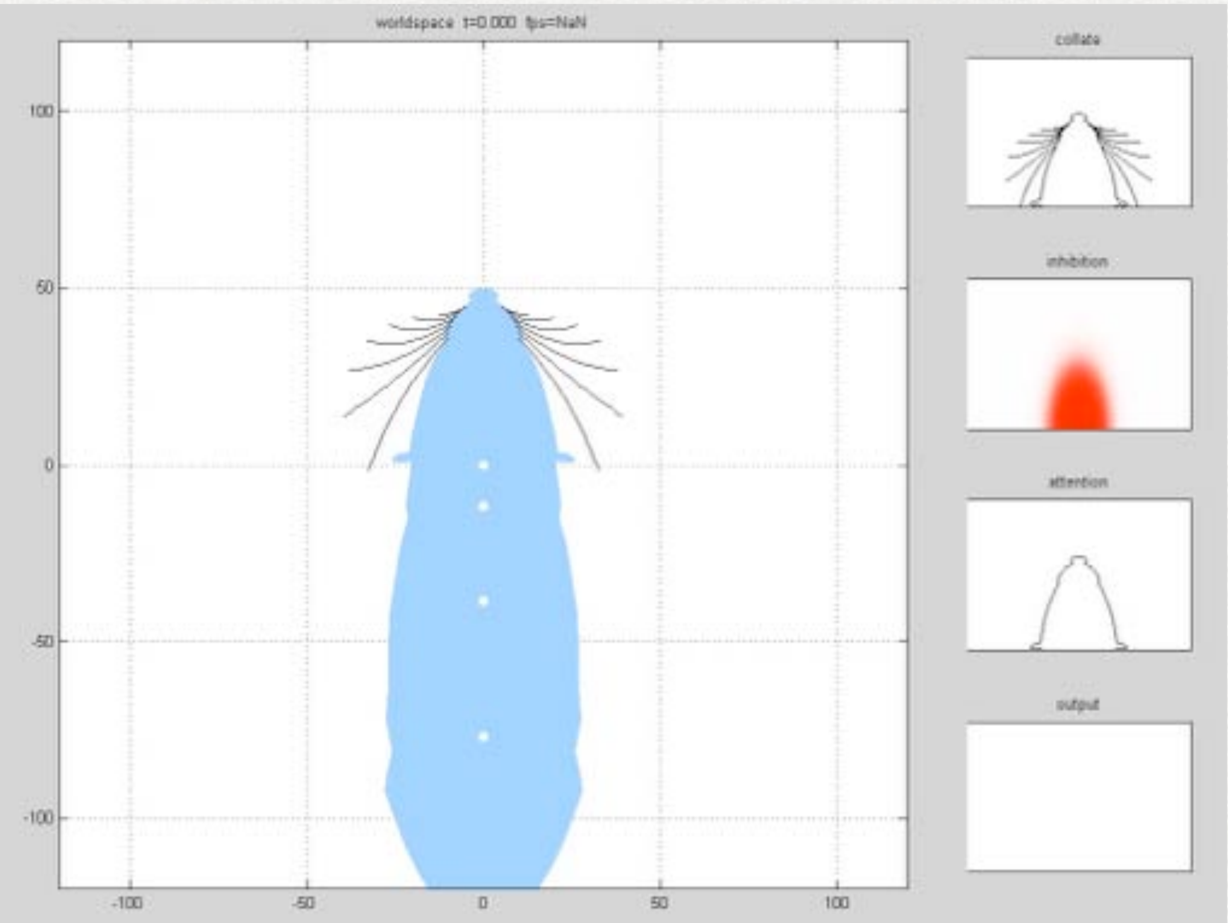
Theories of primate visual attention widely assume that sequences of eye movements are generated by computing viusal salience.

A SALIENCY MAP HYPOTHESIS FOR ACTIVE VIBRISSAL TOUCH

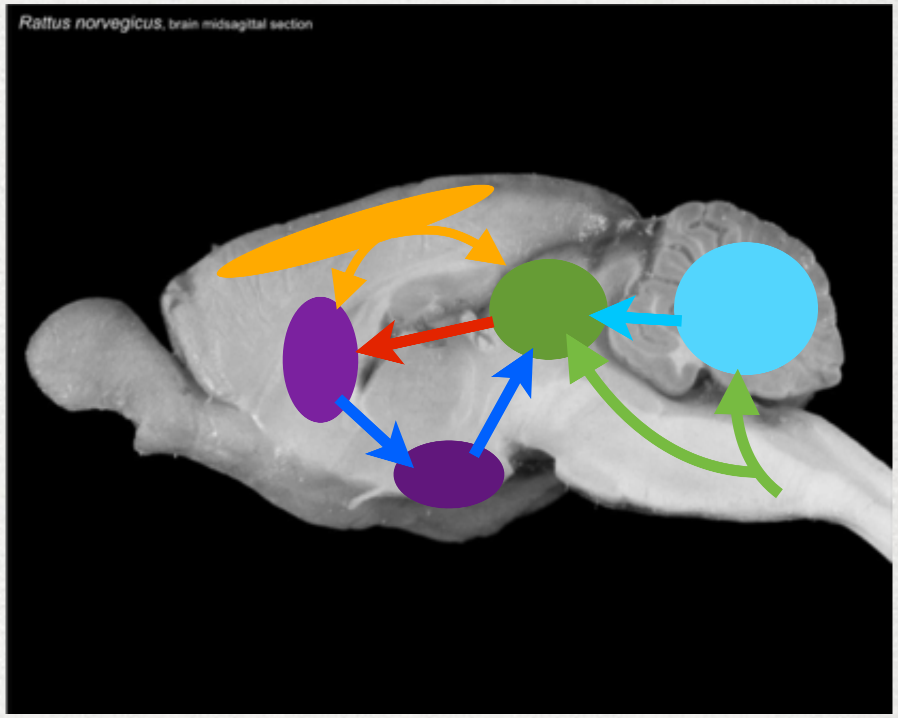
We have proposed that rat brain may compute a salience map for controlling the fine movement and positioning of the vibrissae.

Cortical systems are likely to be involved in computing salience.

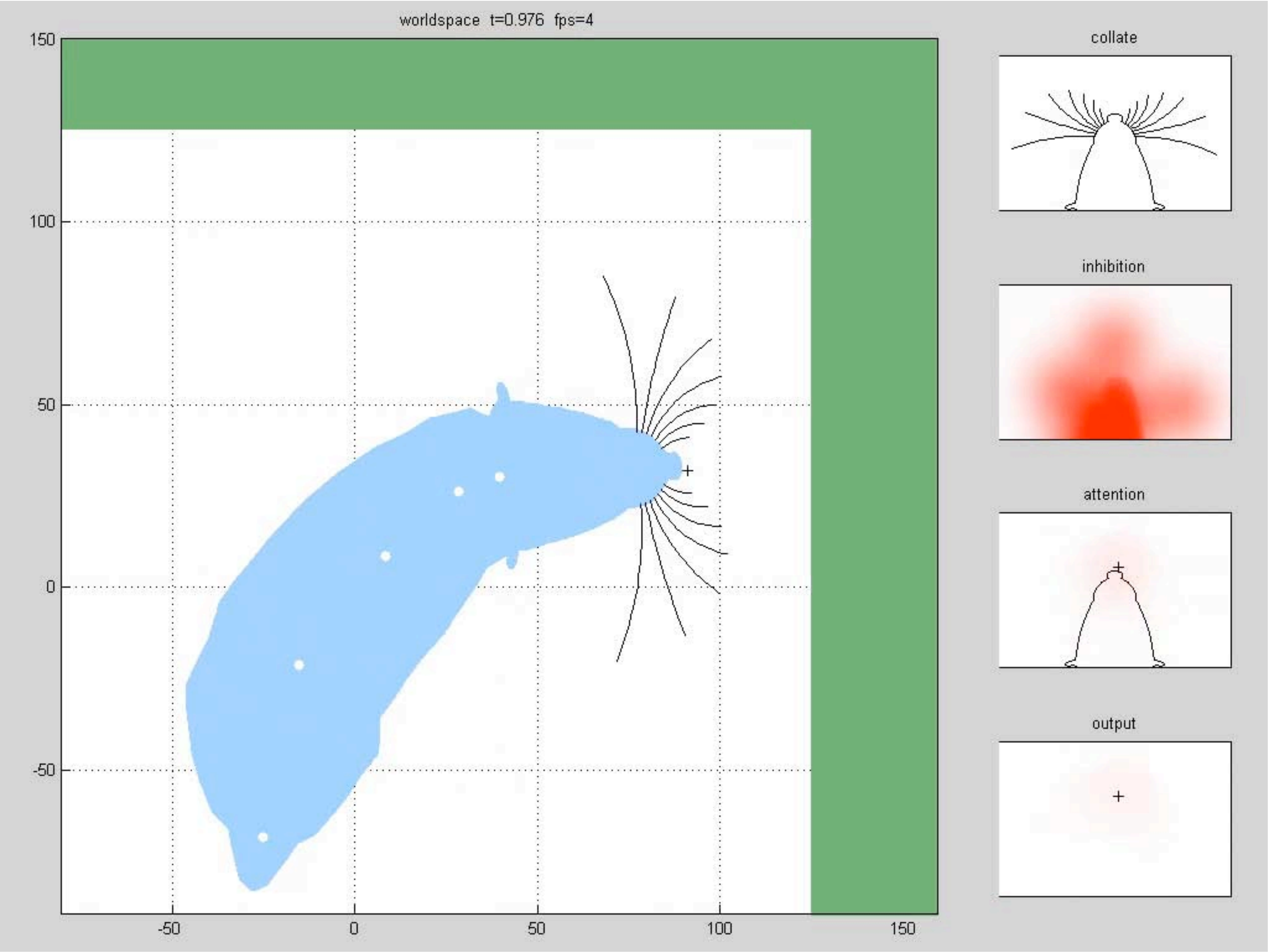




Source: Mitchinson, Ben, and Tony J. Prescott. "Whisker movements reveal spatial attention: A unified computational model of active sensing control in the rat." PLoS Comput Biol 9, no. 9 (2013): e1003236.



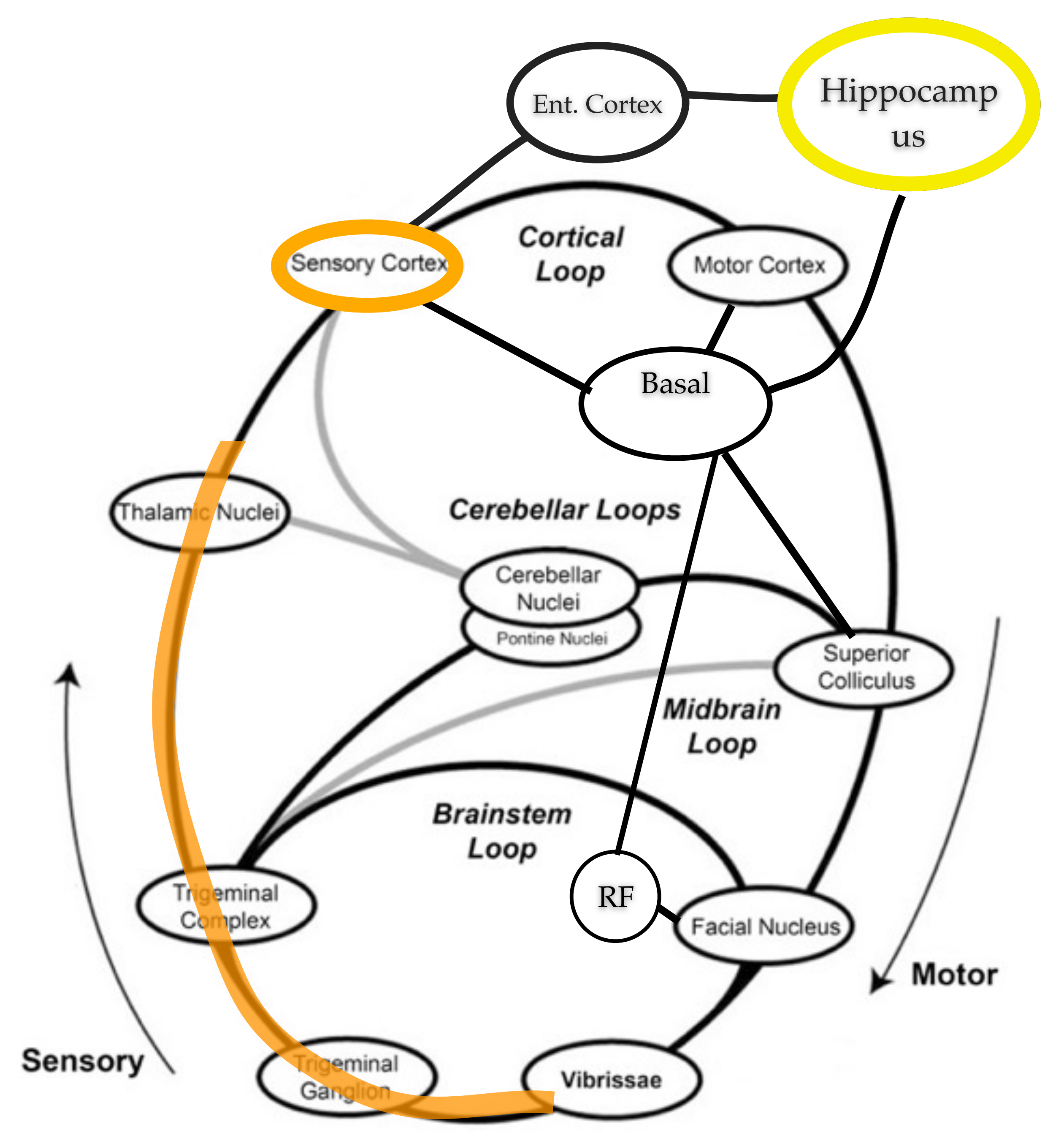
Mitchinson and Prescott 2013. PLoS Comp Bio



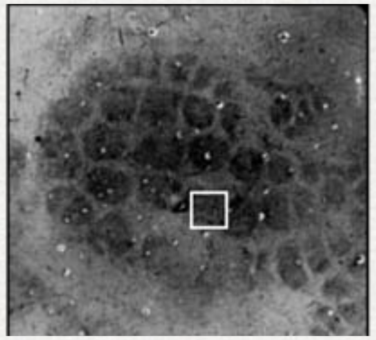
Source: Mitchinson, Ben, and Tony J. Prescott. "Whisker movements reveal spatial attention: A unified computational model of active sensing control in the rat." PLoS Comput Biol 9, no. 9 (2013): e1003236.

ORIENTING AND VIBRISSAL CONTROL IN A WHISKERED ROBOT

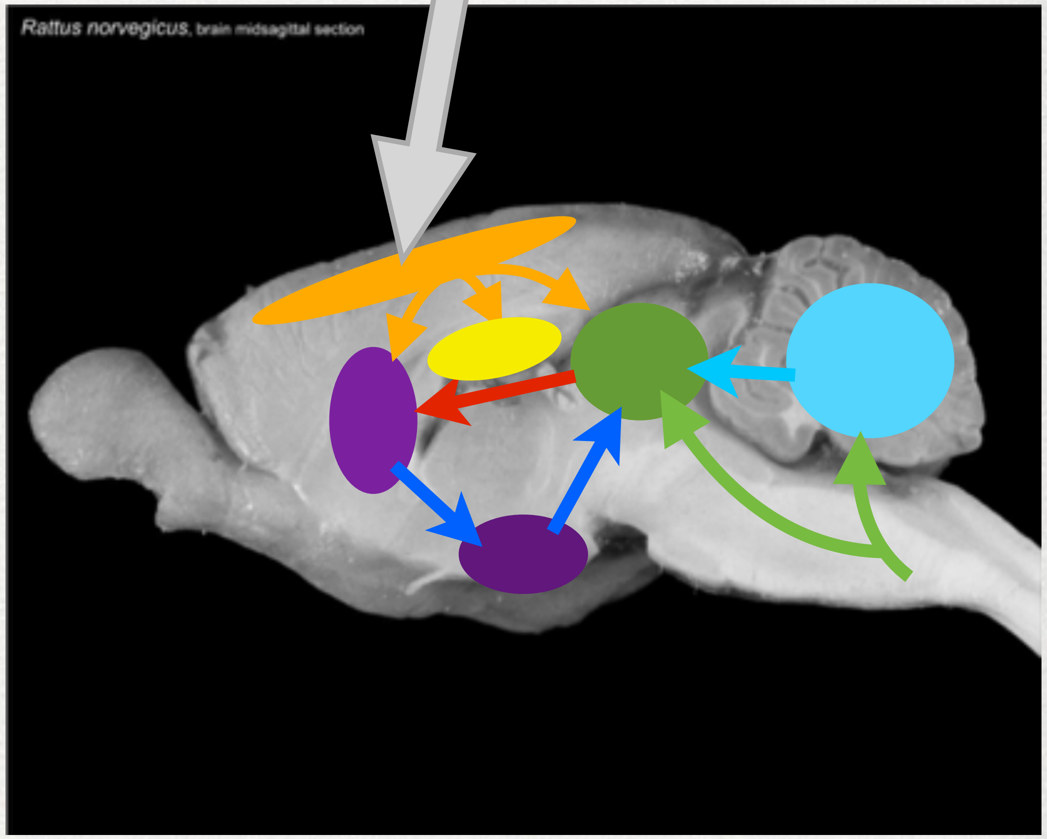
CORTEX & HIPPOCAMPUS



Source: Kleinfeld, David, Ehud Ahissar, and Mathew E. Diamond. "Active sensation: Insights from the rodent vibrissa sensorimotor system." Current opinion in neurobiology 16, no. 4 (2006): 435-444.



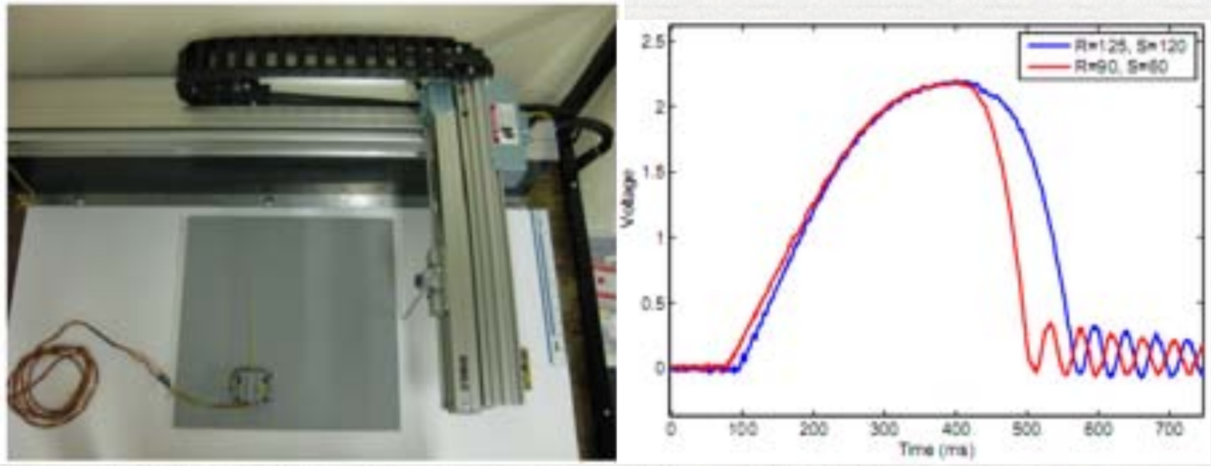
Wilson, Stuart P., Judith S. Law, Ben Mitchinson, Tony J. Prescott, and James A. Bednar. "Modeling the emergence of whisker direction maps in rat barrel cortex." PloS one 5, no. 1 (2010): e8778. https://doi.org/10.1371/journal.pone.0008778. License CC BY.



MODELS OF WHAT & WHERE CORTICAL FEATURE DETECTORS

Classifiers for radial distance, texture and novelty, have been developed and tested on a variety of robot platforms

M.Evans et al. (SAB2010)

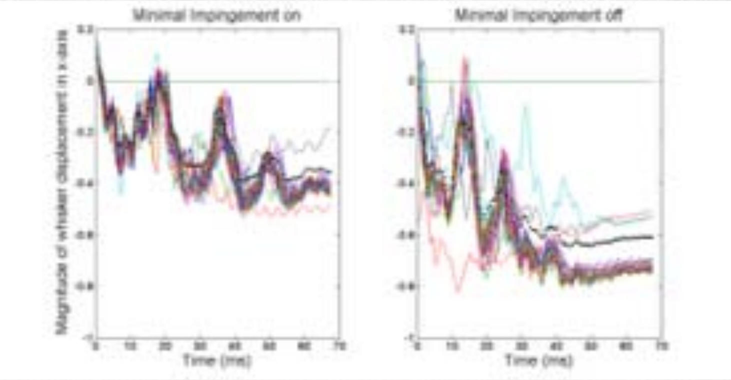


Source: Evans, Mat, Charles W. Fox, Martin J. Pearson, Nathan F. Lepora, and Tony J. Prescott. "Whisker-object contact speed affects radial distance estimation." In Robotics and Biomimetics (ROBIO), 2010 IEEE International Conference on, pp. 720-725. IEEE, 2010.

M.J.Pearson et al. (SAB2010)

Figure removed due to copyright restrictions. Please see the video.

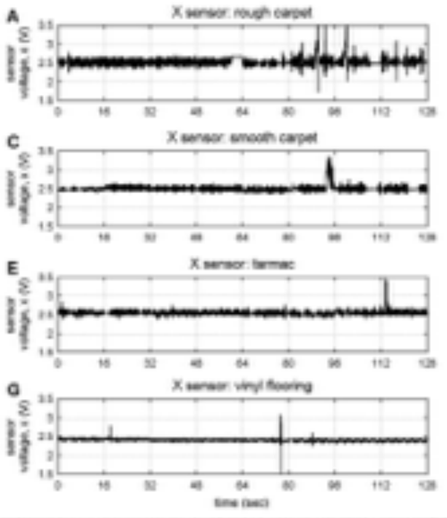
Source: Figure 3 from Pearson, Martin J., Ben Mitchinson, Jason Welsby, Tony Pipe,and Tony J. Prescott. "Scratchbot: Active tactile sensing in a whiskered mobile robot." In International Conference on Simulation of Adaptive Behavior, pp. 93 103. Springer Berlin Heidelberg, 2010.



N.Lepora et al. (WCCI2010)

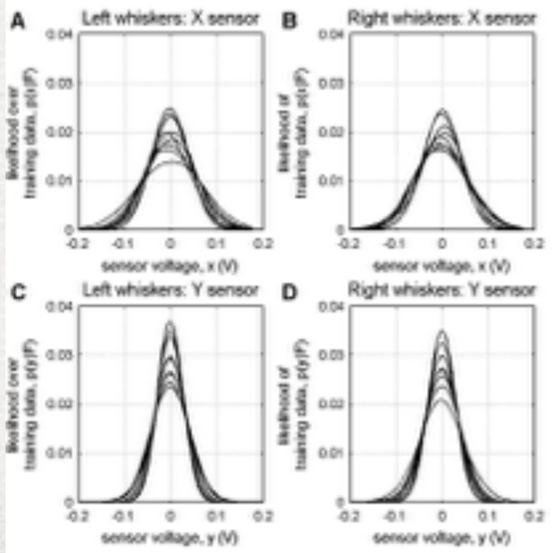
Figure removed due to copyright restrictions. Please see the video.

Source: Figures 1 and 2 from Lepora, Nathan F., Mat Evans, Charles W. Fox, Mathew E. Diamond, Kevin Gurney, and Tony J. Prescott. "Naive Bayes texture classification applied to whisker data froma moving robot." In Neural Networks (IJCNN), The 2010 International Joint Conference on, pp.v1-8. IEEE, 2010.



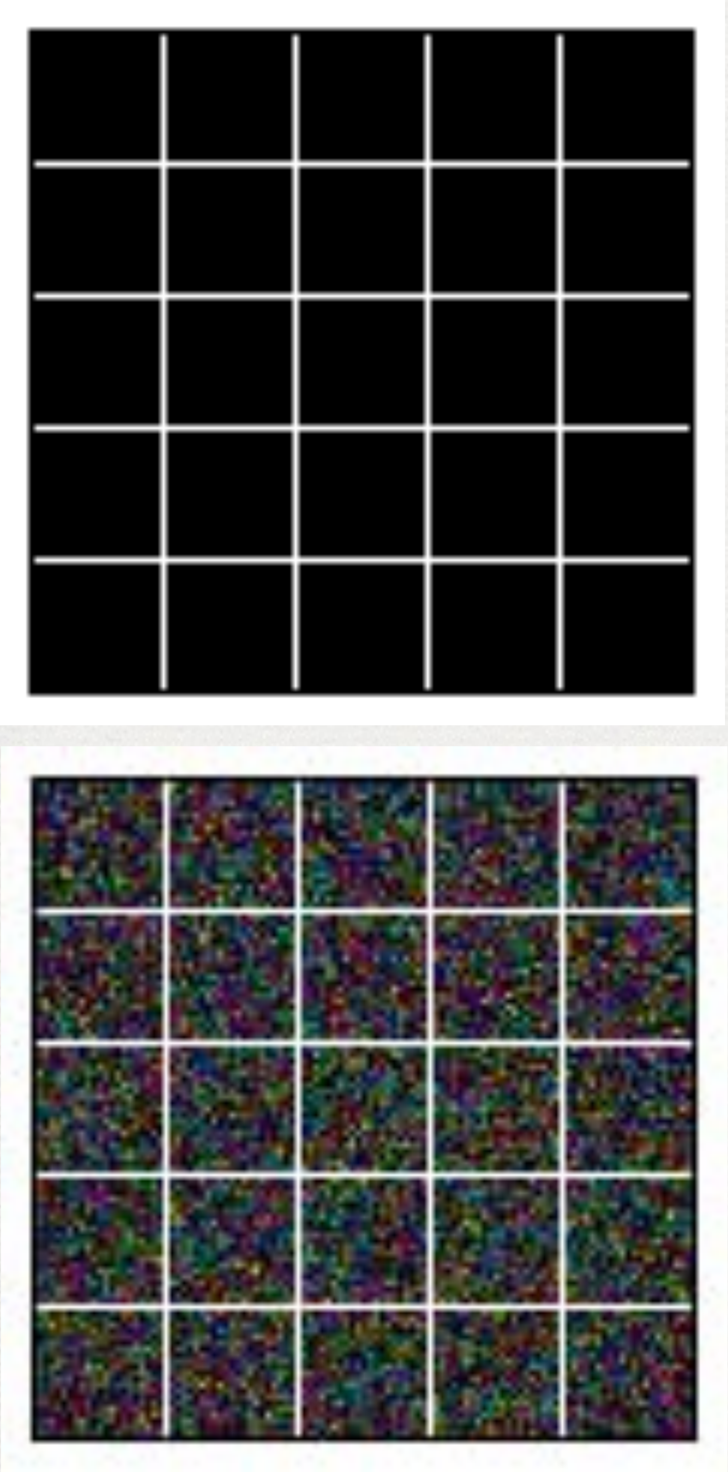
N.Lepora et al. (ROBIO2011)

Figure removed due to copyright restrictions. Please see the video.



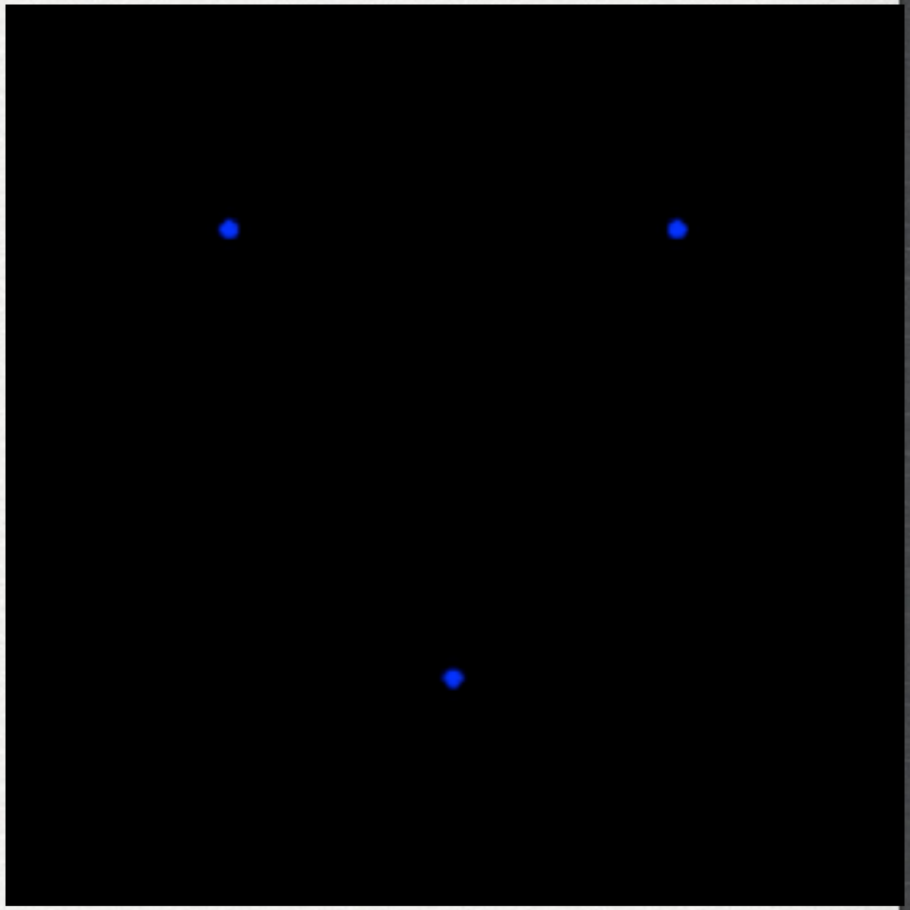
GEOMETRY AS COMPUTATION

We are developing models of self-organisation in barrel cortex as a path towards developing self-constructing controllers for Living Machines. We demonstrate how natural brains exploit geometry to make computation efficient.



Wilson et al. 2010, PLoS One

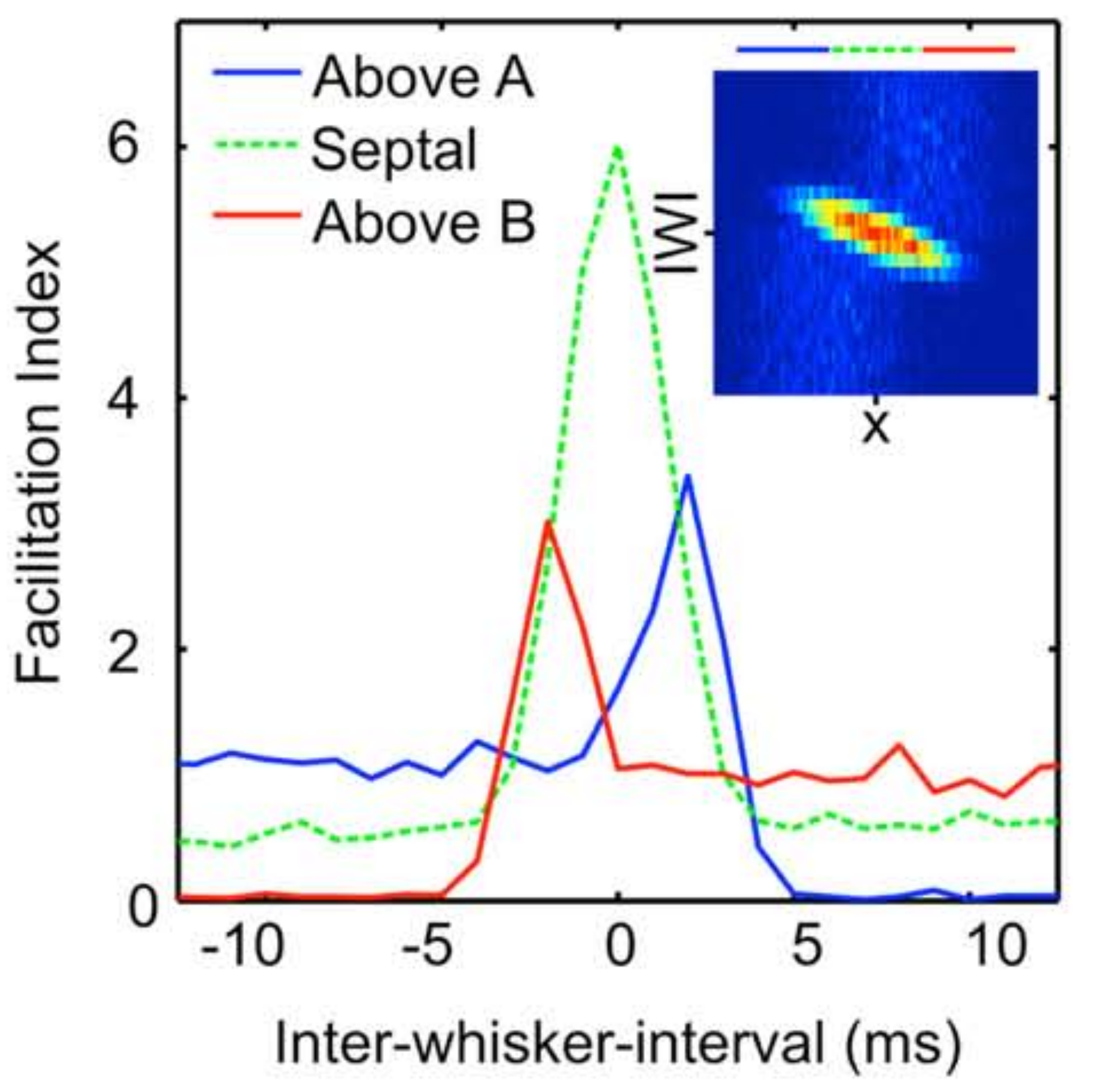
Ferezou et al. 2007, Neuron



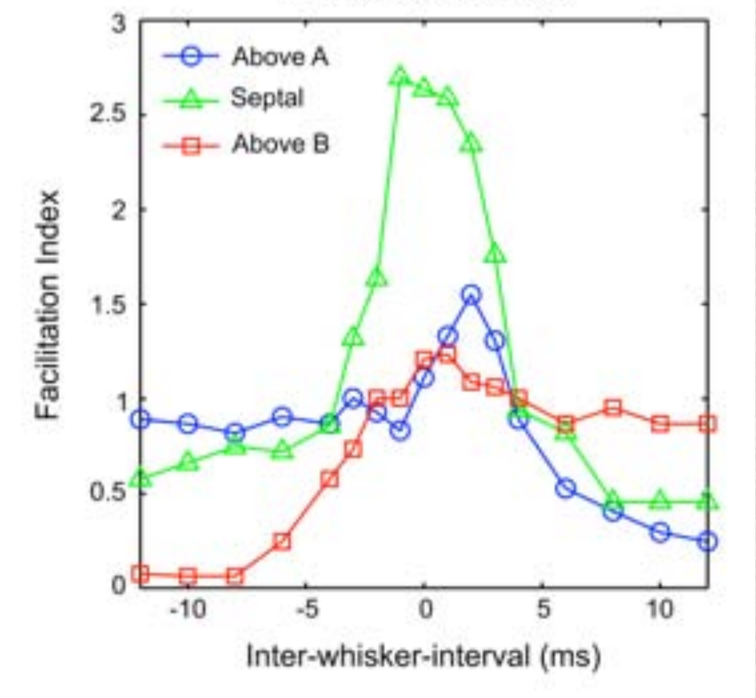
Wilson et al. 2011, PLoS Comp Bio

GOOD MATCH TO DATA ON INTER-WHISKER FACILITATION IN RAT

MODEL



BIOLOGY

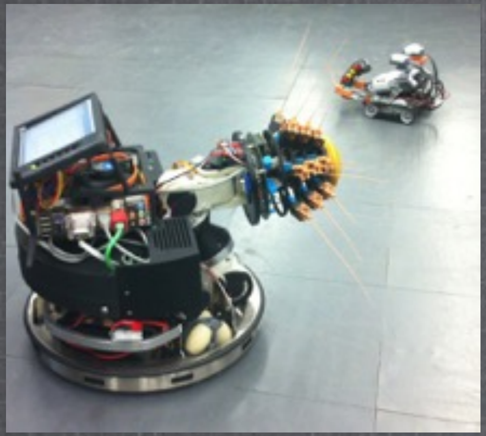


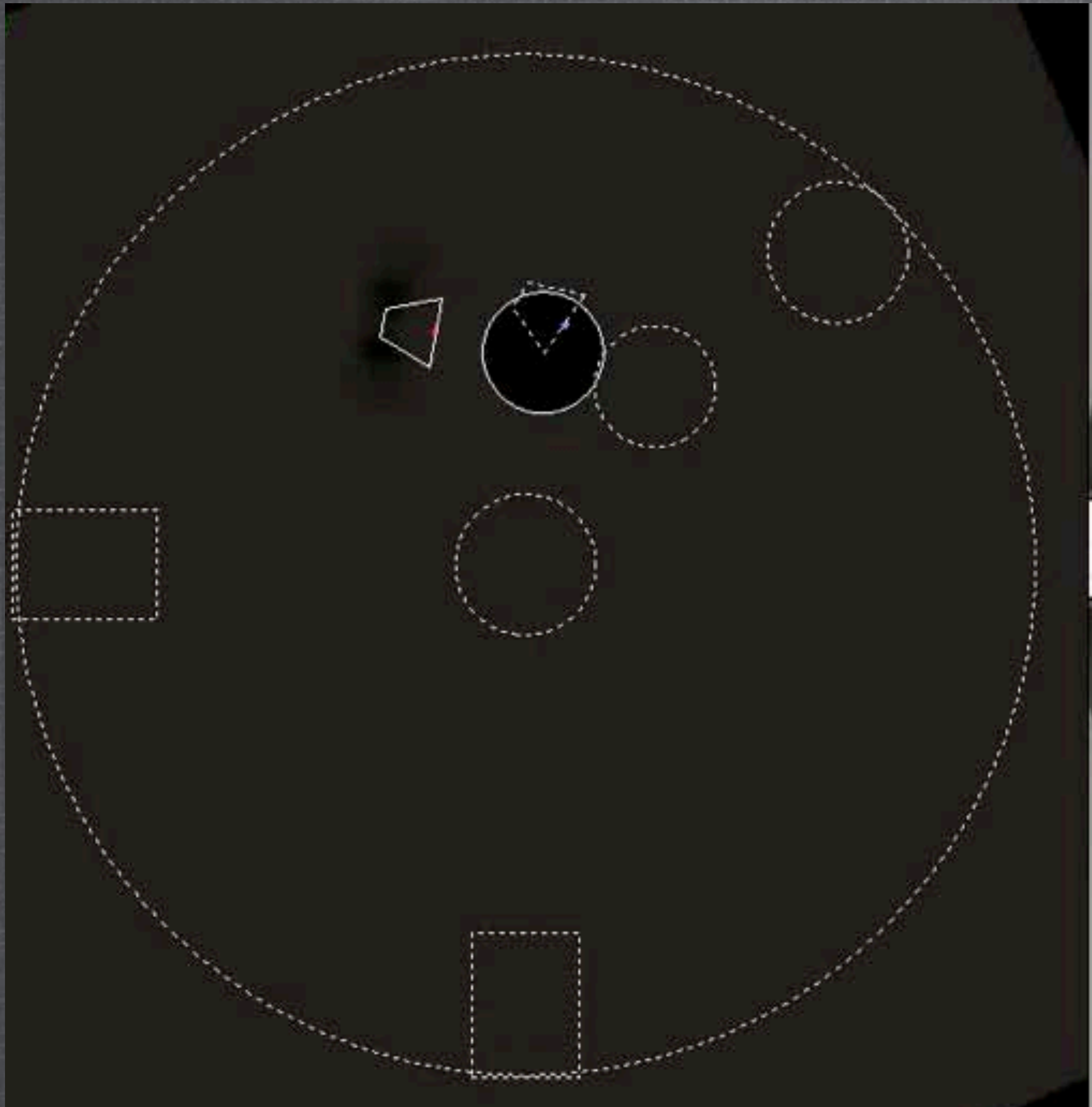
Shimegi et al., 2000

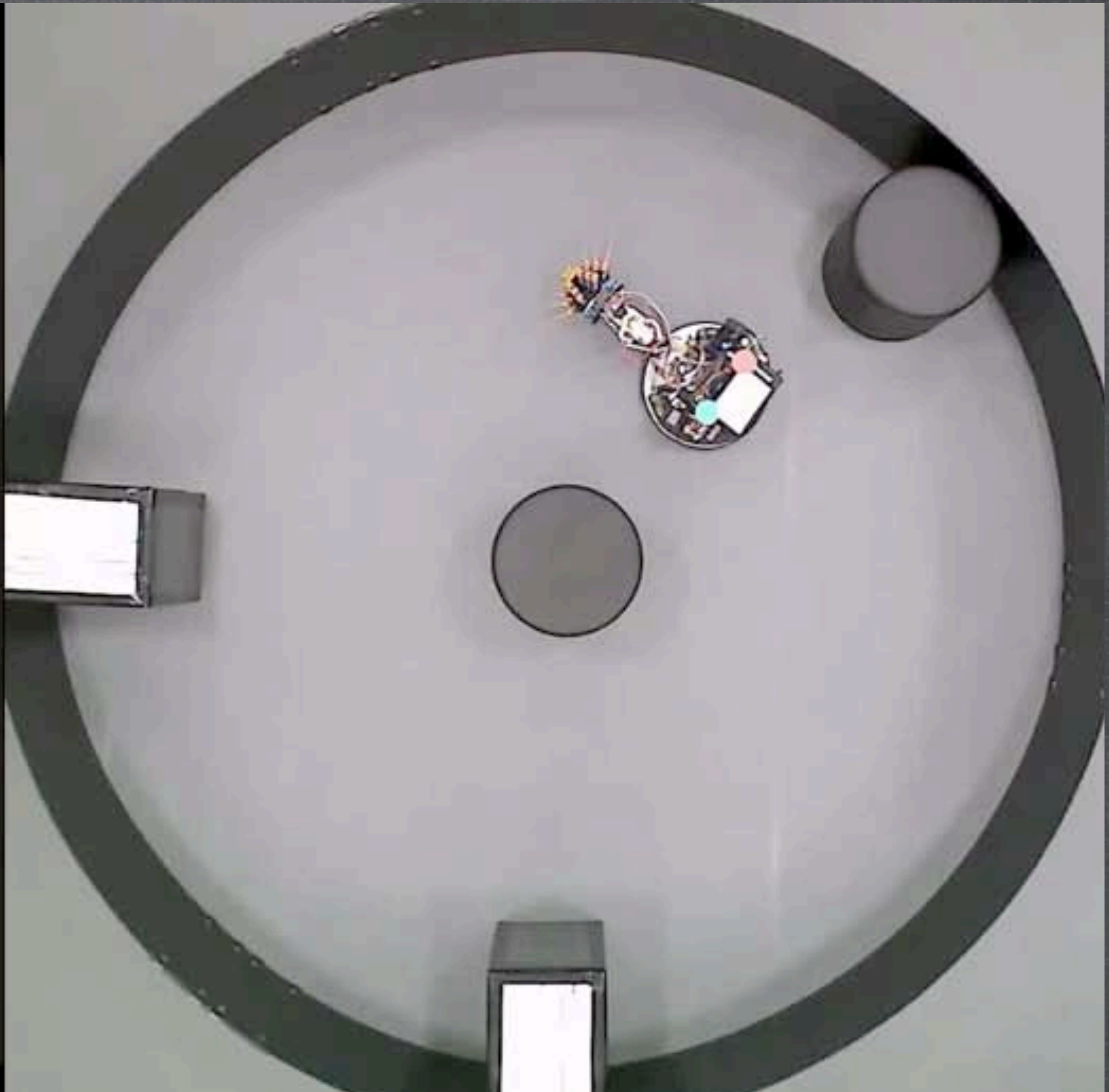
Courtesy of Stuart Wilson, James Bednar, Tony Prescott and Ben Mitchinson. License CC BY.
Source: Wilson, Stuart P., James A. Bednar, Tony J. Prescott, and Ben Mitchinson. "Neural computation via neural geometry: A place code for inter-whisker timing in the barrel cortex?" PLoS Comput Biol 7, no. 10 (2011): e1002188.

Wilson, Prescott, Bednar, Mitchinson, PLoS Comp Bio, 2010

TACTILE SIMULTANEOUS LOCALISATION AND MAPPING







THE ROBOT SELF

New Scientist image removed due to copyright restrictions.
Please see the video or https://www.newscientist.com/article/mg22530130.400-me-myself-and-icub-meet the-robot-with-a-self/.

38 | NewScientist | 21 March 2015

Resource: Brains, Minds and Machines Summer Course
Tomaso Poggio and Gabriel Kreiman