Developmental Robotics:
an emerging paradigm for intelligent agents

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Aims and agenda

- Consider various approaches
- Review concepts and inspiration
- Illustrate with a case study
- Observations
- Persuade you that development is necessary for embedded learning systems

Issues

- Why development?
- Why infants?
- Why robots?

Some current approaches

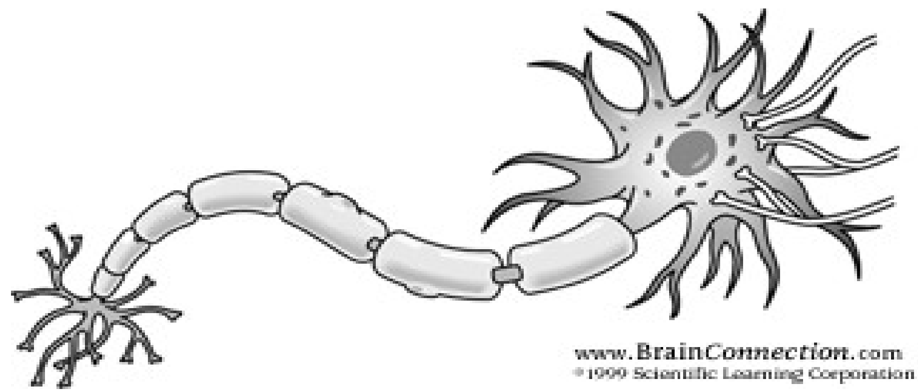
- Cognitive Science
- Connectionism
- Cognitive robotics
- Developmental approach
- Mechanism mapping
- Mechanism mining.

Cognitive science

- Memory, reasoning, perception, language
- Computing paradigms
- Rule-based, Soar, ACT
- Modular, architectures, structures
- Tends to impose computing models.

Connectionism (1)

- A challenge to the idea of separate process and memory
- Mainly artificial neural networks (ANNs)
- Highly parallel, adaptive, fast
- But “model-free statistical function estimators”.


www.BrainConnection.com
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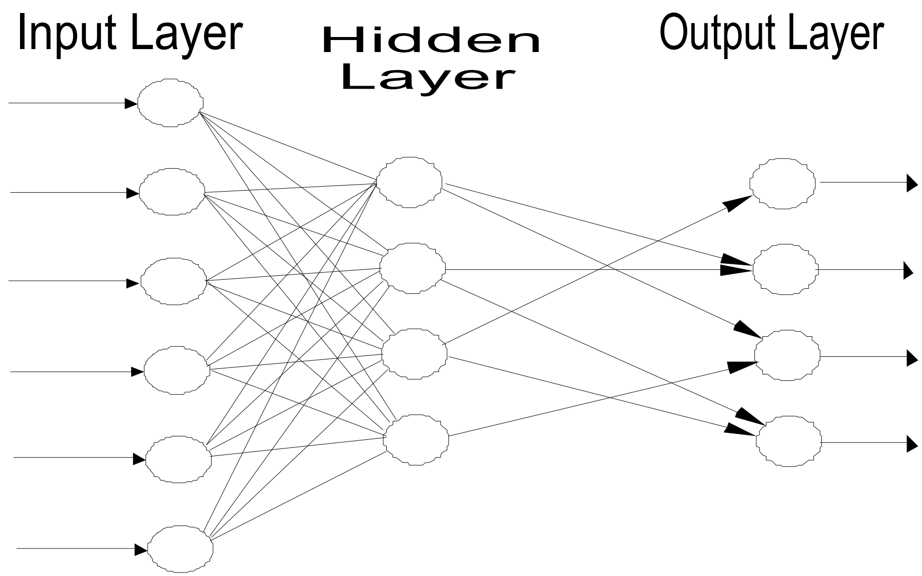

Input Layer
Hidden
Layer
Output Layer

Connectionism (2)

- Large training phases - unrealistic
- Supervised - unrealistic
- Black box (attractive for some)
- Newer neuron models very detailed
- Population simulations impressive
- Dogma of neural models.

Cognitive robotics

- Logical foundations - e.g. situation calculus
- Knowledge based - but decision theoretic, e.g. “Expectation and Feedback as Hypothetico-Deduction”
- Strictly logical - exclusively so
- Not really robotics - ignores sensory/motor
- Not really cognitive - ignores sensory/motor
- High level, abstract, and symbolic.

Psychological (developmental) approach

- High level - but behavioural data
- Reflect bio/psycho constraints
- Abstract computational models
- Can map onto neural substrate
- Synthesis process - vis Braitenberg.

Mechanism mapping

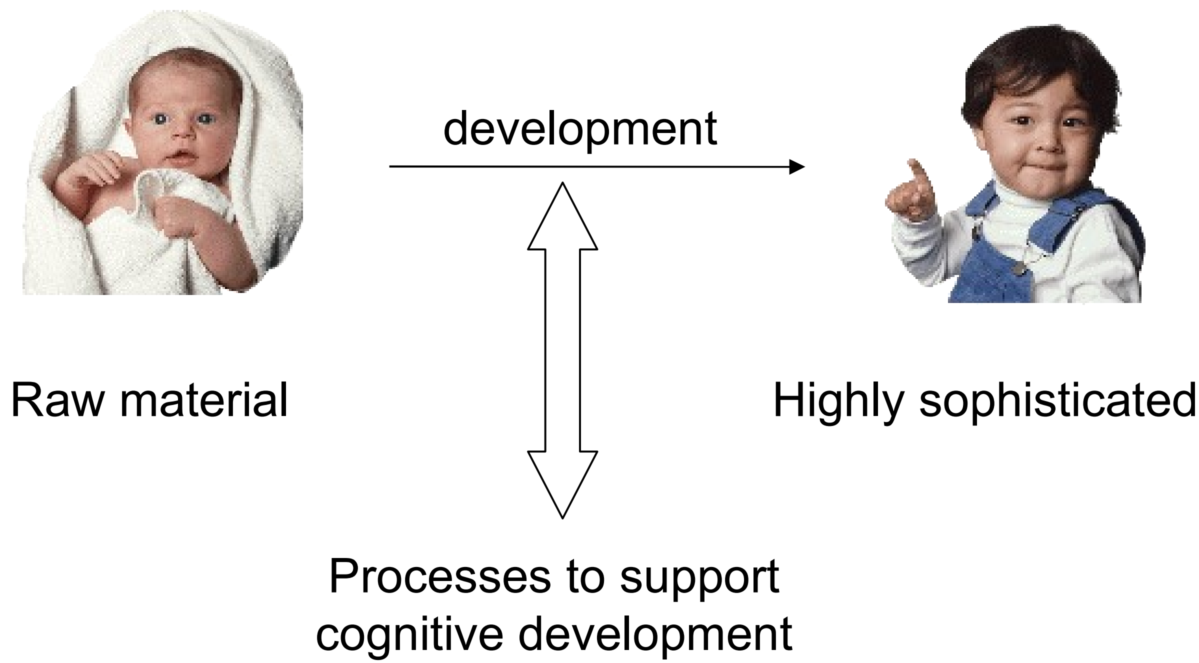
- Top-down
- Scientific analysis
- Artificial -> biological
- Validation against biology
- Analysis, refinement cycle.

Mechanism mining

- Bottom up
- Inspired invention
- Biology -> mechanism
- Biological constraints - guidance
- Synthesis, simulate cycle.

Inspiration

Early Infant Development



Alan Turing

"In the process of trying to imitate an adult human mind we are bound to think a good deal about the process which has brought it to the state that it is in."

A.M. Turing, Mind, 59, 433-460, 1950.

Turing quotes (1)

“Instead of trying to produce a programme to simulate the adult mind, why not rather try to produce one which simulates the child's? If this were then subjected to an appropriate course of education one would obtain the adult brain.”

“We have thus divided our problem into two parts. The child programme and the education process. These two remain very closely connected.”

“Opinions may vary as to the complexity which is suitable in the child machine.”

Jean Piaget's **four stages of human cognitive development**

Sensorimotor(0-2): not capable of symbolic representation.

Preoperational(2-6): Egocentric, unable to distinguish appearance from reality; incapable of certain types of logical inference.

Concrete operational(6-12): capable of the logic of classification and linear ordering.

Formal operation(12-):capable of formal, deductive, logic reasoning.

Infant stages

1 month - stare at bright objects. Hands normally closed but, if open, grasps when palm touched.

3 months - visually very alert, gaze follows toy. Hand regard, clasp/unclasp. Holds toy but not eye coordinated.

Infant stages

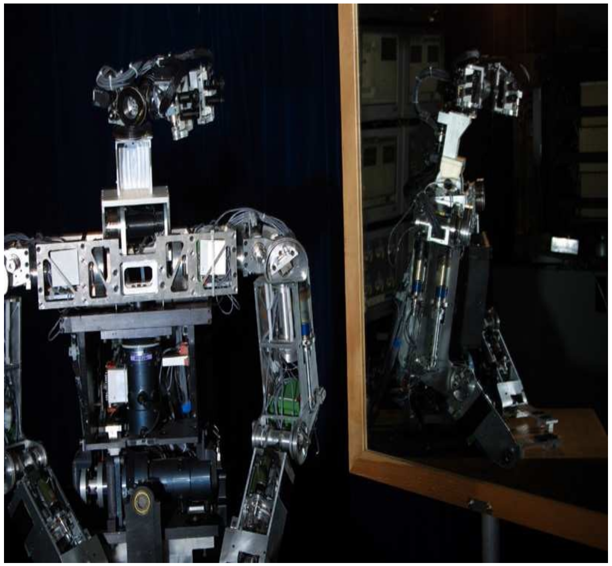
6 months - visually insatiable, follows adults/toys, stares at small objects and tries grasp with both hands. Palmar grasp. Searches inexpertly when toy lost. Takes all to mouth.

Developmental Robotics

- Multidisciplinary research area
- Mostly inspired by developmental psychology
- Considerable emphasis on sensory-motor interaction
- Embodied (simulation frowned on)
- aka: epigenetic, life-long learning …

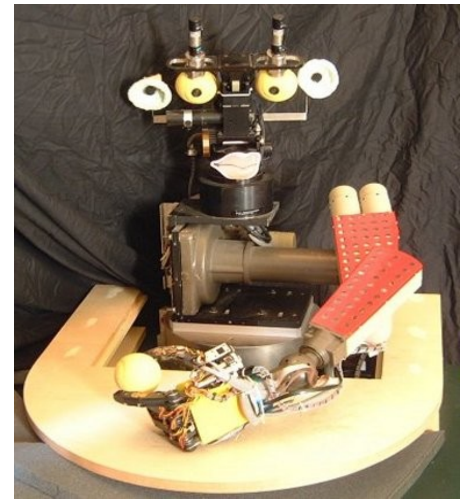
Approach

Examples of systems used in robotic developmental learning



Cog, MIT, USA

Infanoid, CRL, Japan



BabyBot, Genoa, Italy

SAIL, MSU, USA

DVL, UWA, Wales

Embodiment

"…, cognition depends upon the kinds of experiences that come from having a body with particular perceptual and motor capabilities that are inseparably linked and that together form the matrix within which reasoning, memory, emotion, language, and all other aspects of mental life are embedded."

E. Thelen, Infancy, 1(1), 3-28, 2000

DVL project (EPSRC)

Developmental Learning Algorithms for Embedded Agents

- Psychology, rather than neuroscience
- Abstract models, as far as possible
- But biologically compatible ...
- Assumptions - explicit and compatible with psychological data
- But not psychological modelling - aim is algorithms for robotics.

Constraints

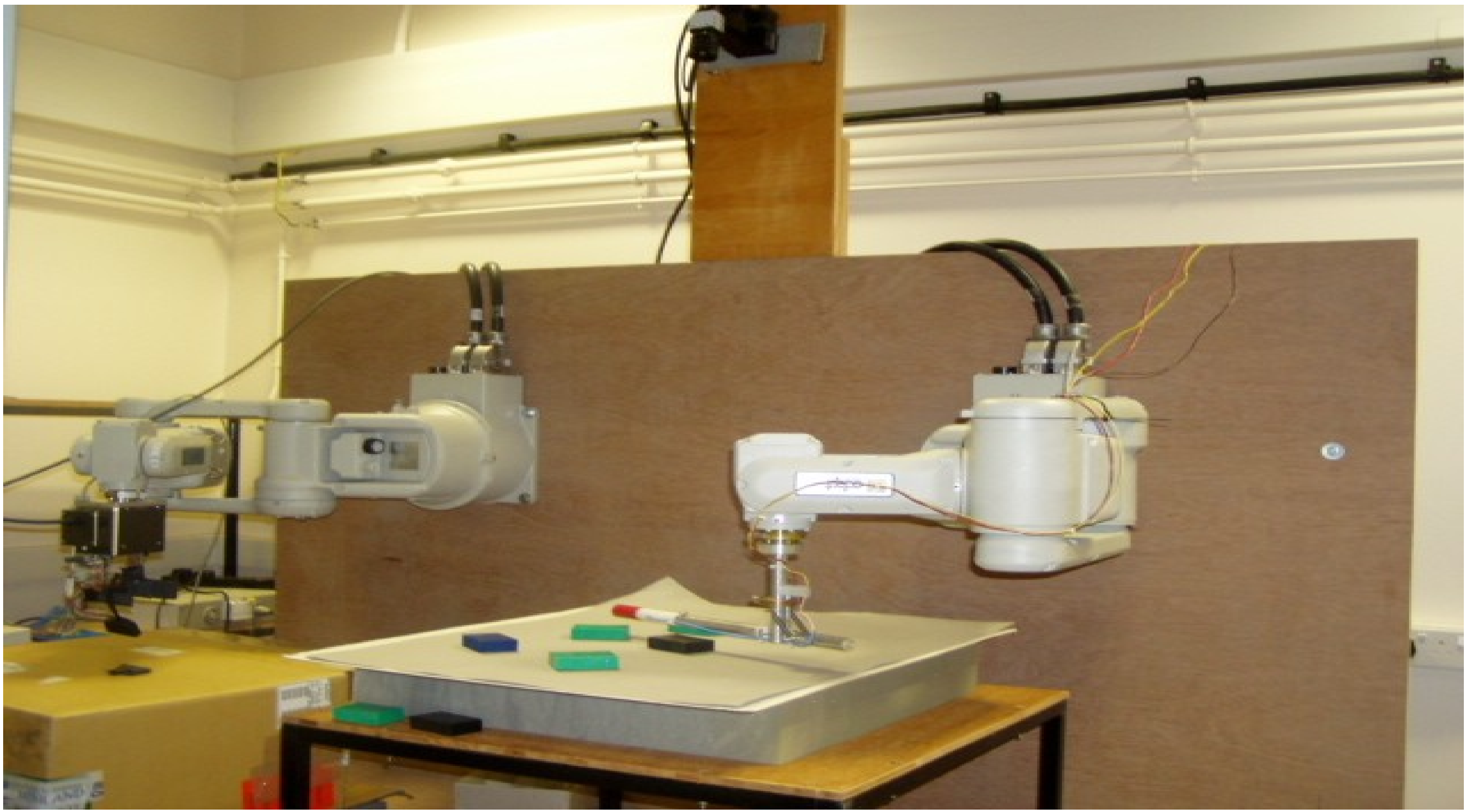
- Staged growth of competence
- Constraints are important
- Constraints are helpful !
- Many forms of constraint:
  – Physical - morphology, mechanical, motor
  – Internal - cognitive, sensory, neural, maturational
  – Environmental - external, scaffolding, social.

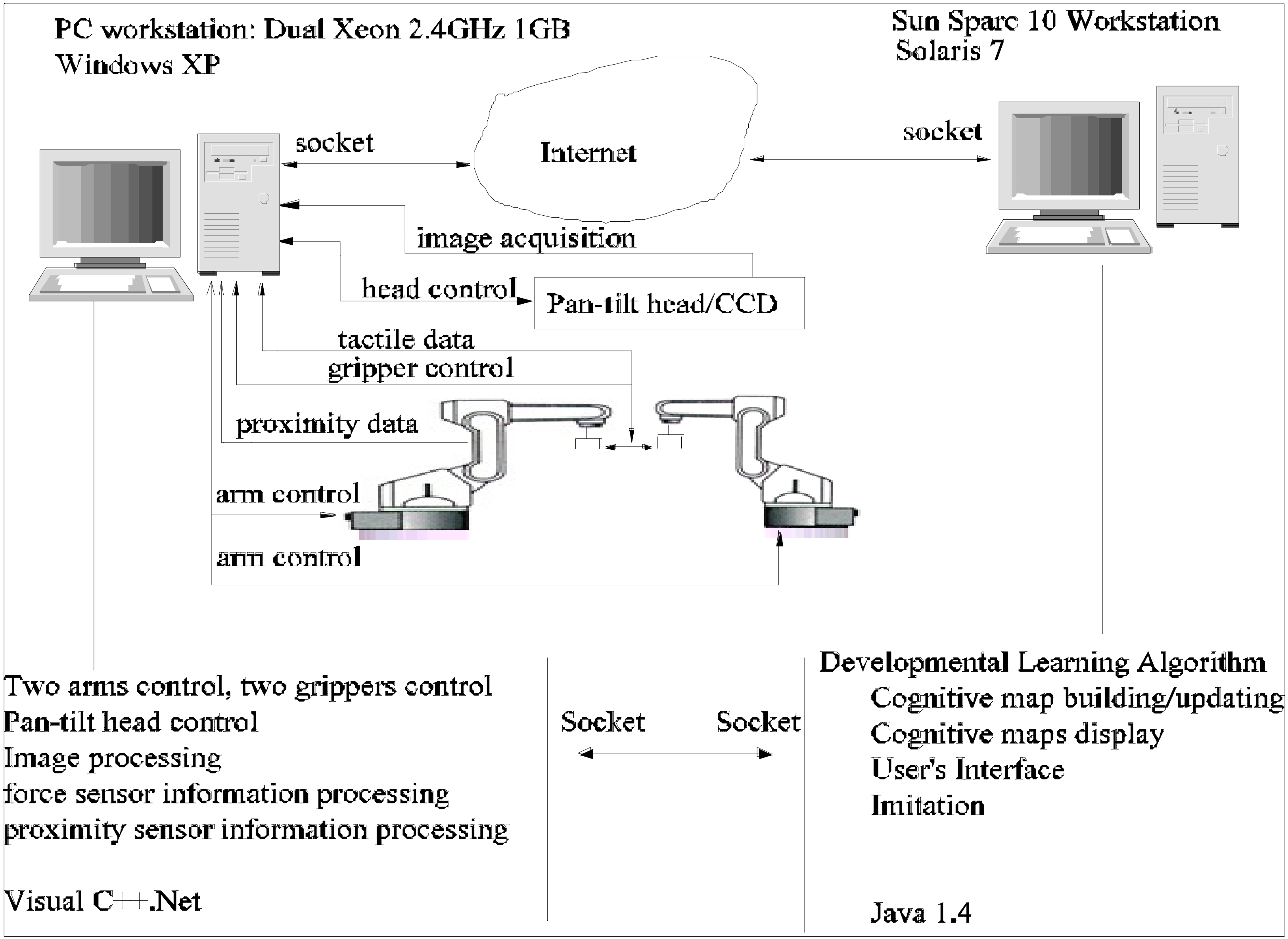
Issues to investigate

- Proprioception encoding - how can space be learned?
- Motor control - how can new actions develop?
- Coordination - intra modal and cross-modal
- Constraint schedules - how should constraints be exploited?

Experiments

Our Experimental Developmental Learning System

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Windows XP
Sun Sparc 10 Workstation
Solaris 7
socket
Internet
socket
image acquisition
head control
Pan-tilt head/CCD
tactile data
gripper control
proximity data
arm control
arm control
Two arms control, two grippers control
Pan-tilt head control
Image processing
force sensor information processing
proximity sensor information processing
Visual C++.Net
Socket
Socket
Developmental Learning Algorithm
Cognitive map building/updating
Cognitive maps display
User's Interface
Imitation
Java 1.4

Sensory-motor spaces

- Two Arms, each with:
  - Motor drives at the joints,
  - Proprioceptive sensing of joint angles
  - Tactile sensing of object contact
- One Eye, with:
  - Retinal axes
  - Foveal feature extraction
  - Motor pan and tilt drives.

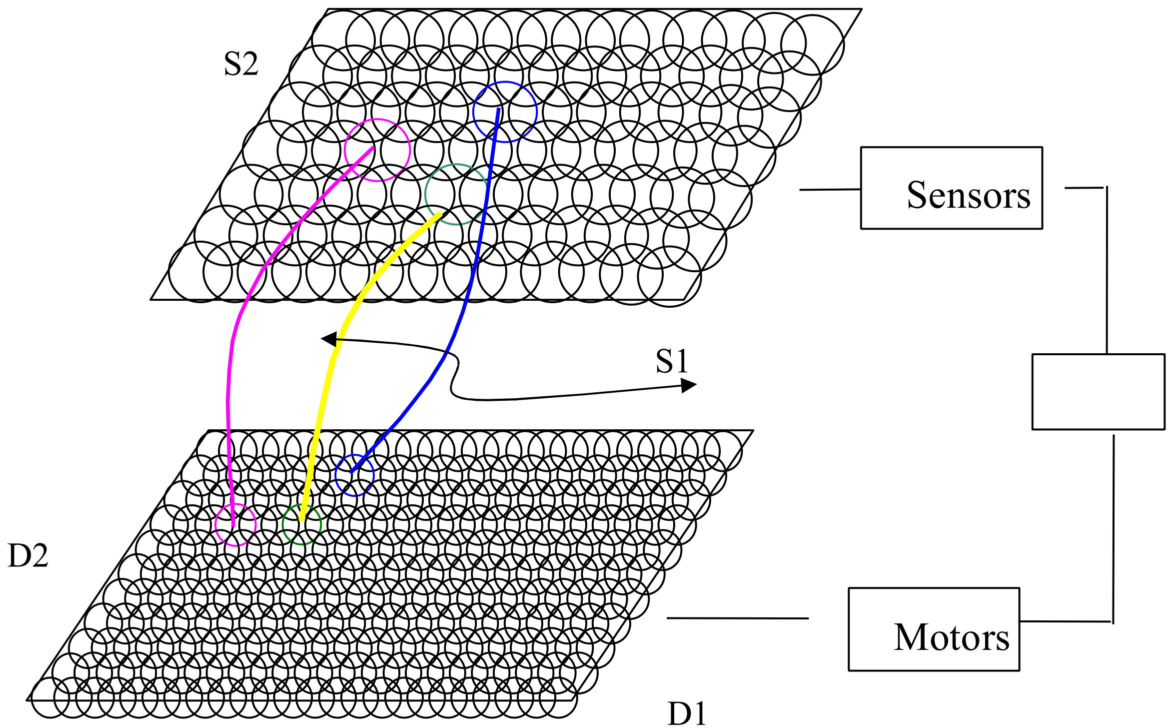
Experimental variables

- Internal/environmental constraints
- Proprioception encoding schemes
- Proprioception resolution
- Novelty/habituation parameters.

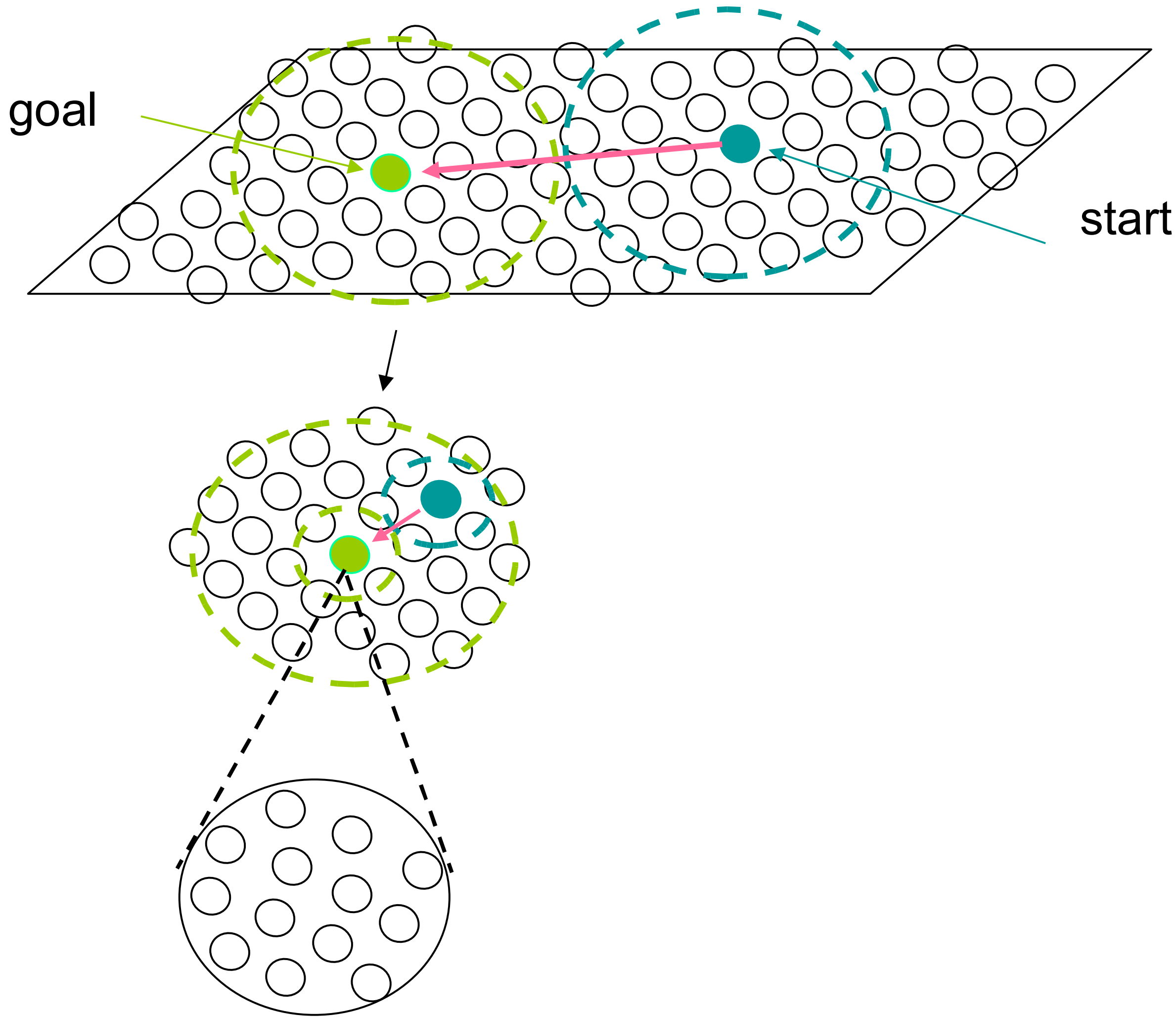
S-M mappings

- Mappings as a computational substrate for sensory-motor learning
- Based on **fields** - overlapping patches of S-M space. Each has stimulus data, excitation levels, habituation values
- Global signals are summations of field values across a map.

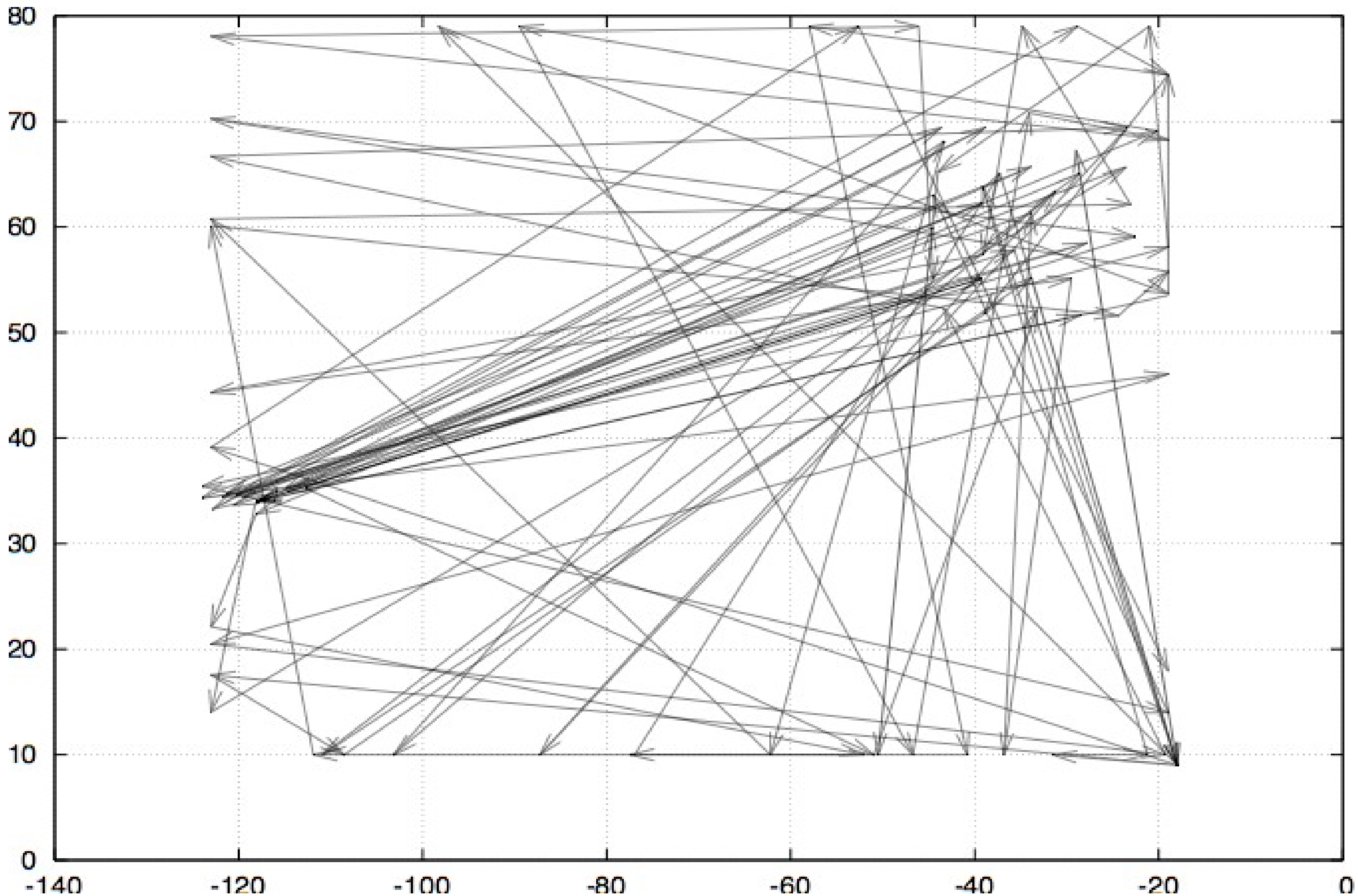
Sensory-motor mapping system



Variable field sizes and hierarchical maps



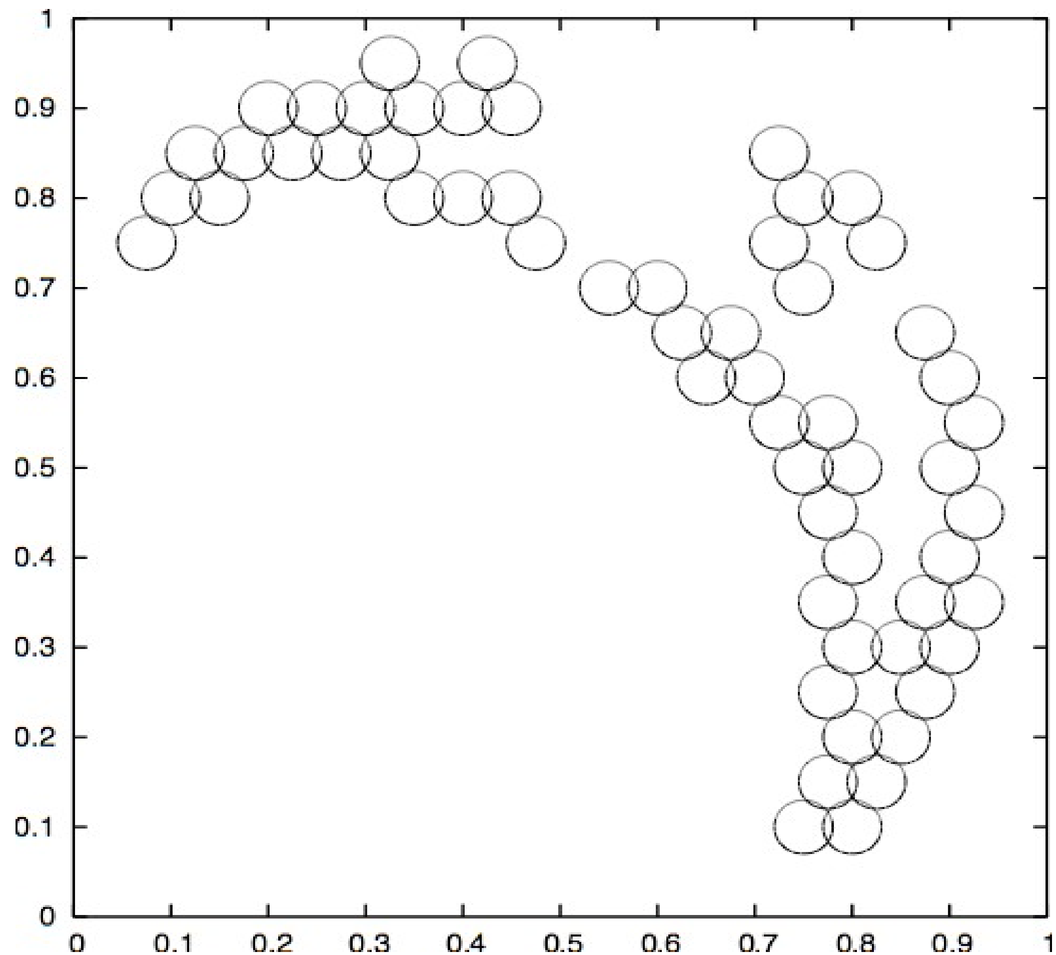
Early actions



Proprio-motor correlation

- While this is happening, the mapping system records the correlation between the D and S values
- When the map is fully/partially developed it will associate changes in sensory locations with motor acts.

Growth of fields



Behaviour types

1. “blind groping” actions mainly directed at the body area
2. more groping but at the boundary limits
3. unaware pushing of objects out of the local environment
4. limb movements stop upon object contact
5. repeated cycles of contact and movement, i.e. “touching” of detected objects
6. directed touching of objects and sequences of objects.

Staged development

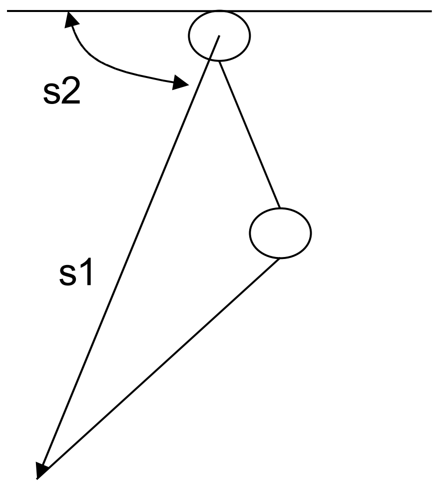
- Hand “grope” creates local space map
- Hands contact objects - sensitive grope
- Eye stimulation creates local visual map
- Eye sees hands - hand fixation
- Hands follow eye fixations
- Grasping of objects.

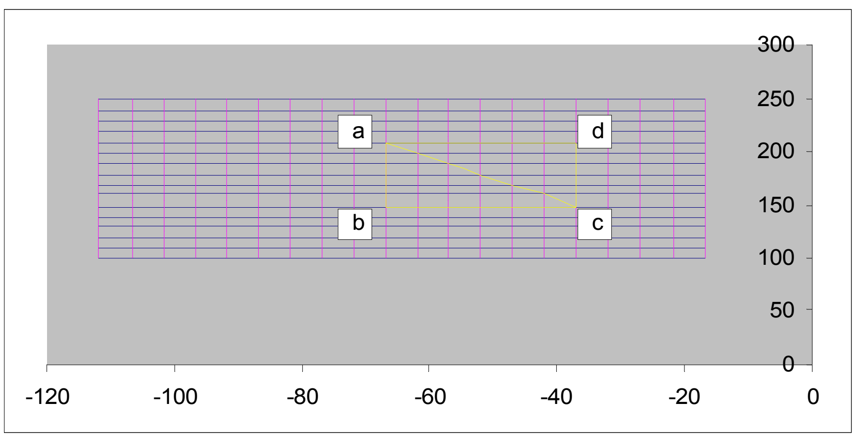
Observations

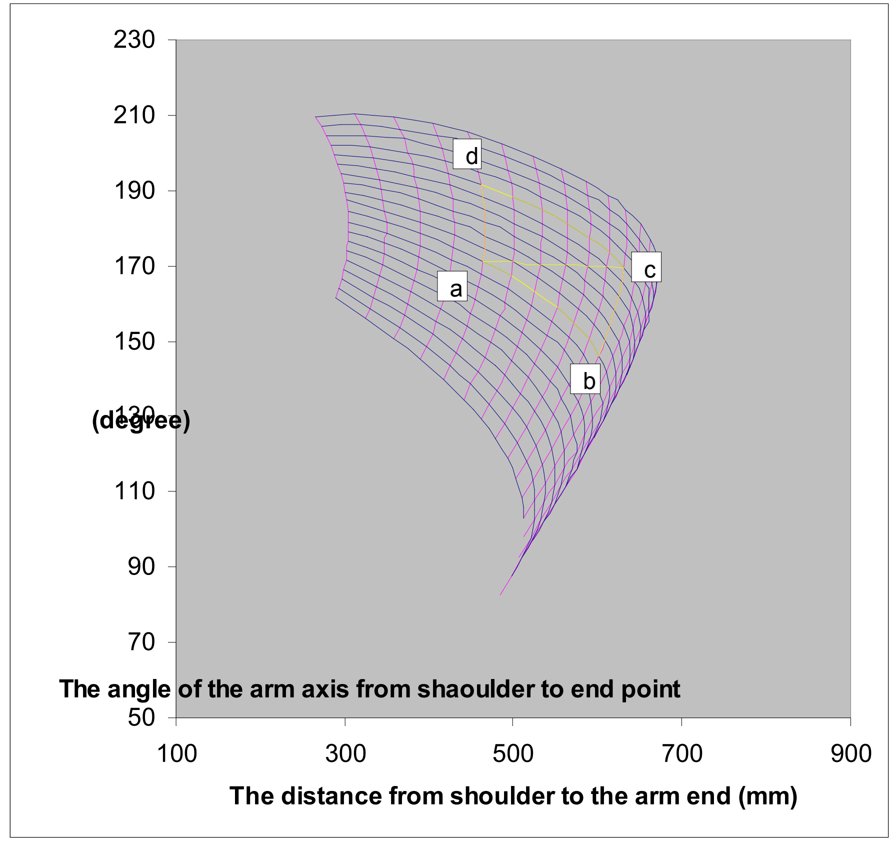
Proprioception encoding

- 4 schemes tested:
  - joint, shoulder, body, Cartesian
- None critical: but body and Cartesian common for both arms, and eye
- Muscle spindle stretch better than joint receptors.
- Mix of receptors ideal for spatial encoding (cf. Bosco *et al*, J. Neurophysiol. 2000)

Shoulder encoding







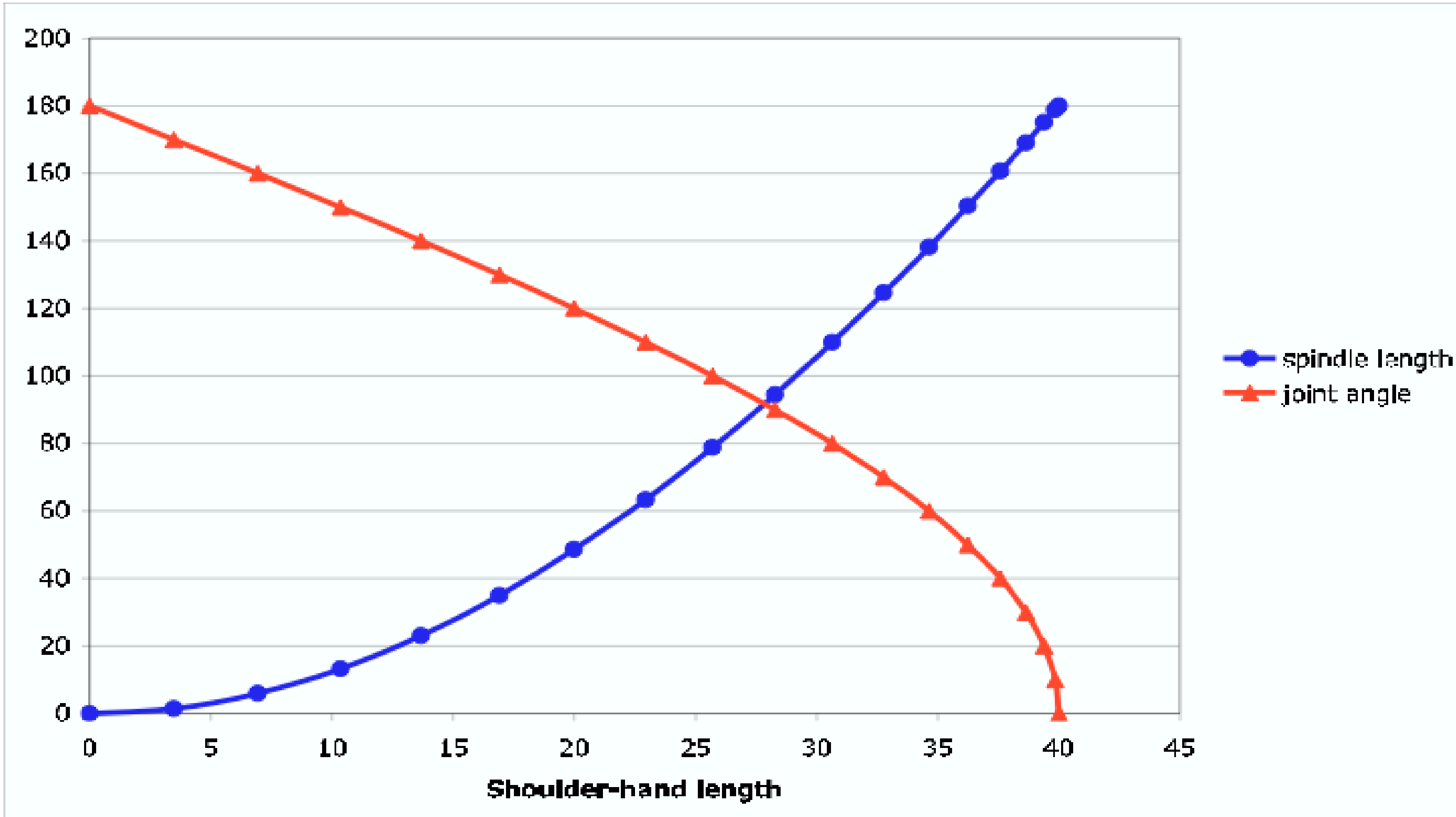
Arm kinematics

Reach = $\sqrt{(\mathbf{l}_1 + \mathbf{l}_2 + 2\mathbf{l}_1\mathbf{l}_2\cos\theta_2)}$

Angle = θ_1 - $\arctan(\mathbf{l}_2\sin\theta_2 / \mathbf{l}_1 + \mathbf{l}_2\cos\theta_2)$

for limb lengths, $\mathbf{l}_1$ $\mathbf{l}_2$ and joint angles, θ_1 θ_2

Joint or muscle?

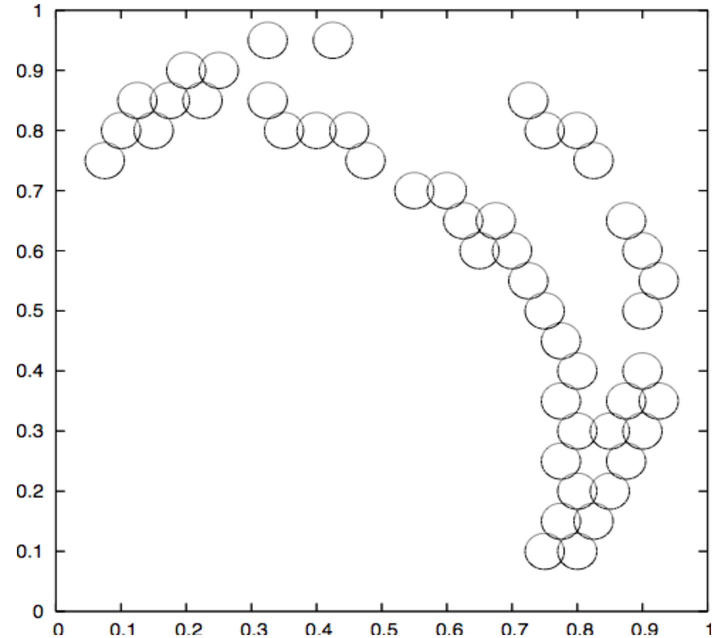


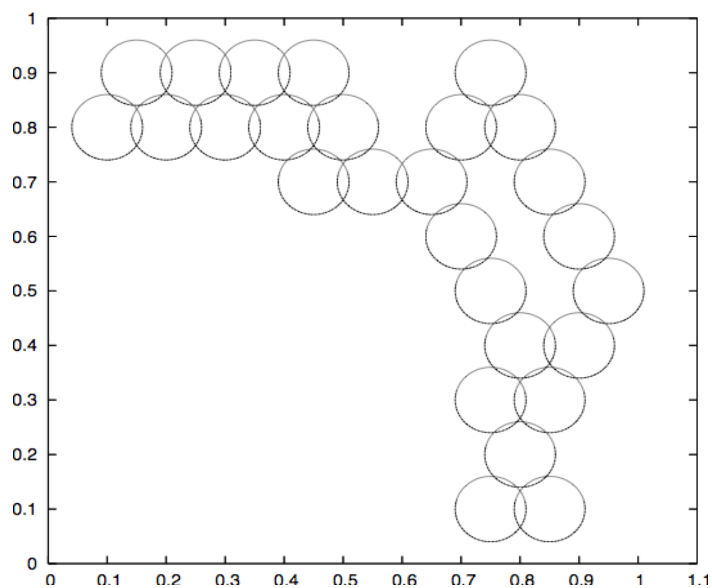
Morphology is important

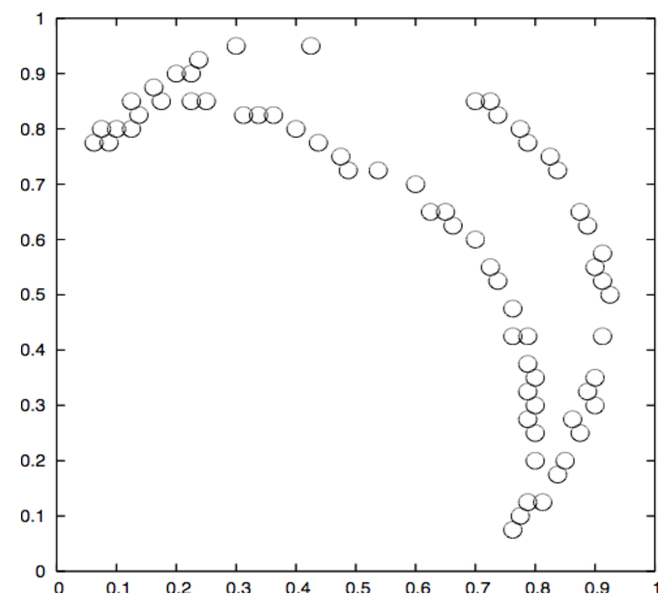
- The physical structure of the agent is a key determining factor.
- Sensory structure determines capacity and capability of sensing modalities.
- Mobility, dexterity, effect, all depend upon appropriate anatomy or hardware.

Sensory resolution

(re Westermann & Mareschal, Infancy, 2004)







Observations (1)

- Spontaneous action can be useful for gaining information, but can also be an indication of reduced learning activity
- Motor noise (and other noise) can be beneficial in early learning
- Low accuracy/resolution can be beneficial in early learning.

Observations (2)

- Proprioception may be more important for supporting vision than previously thought. In particular, non-visual reaching can be developed prior to visually guided grasping. (re: Clifton et al, “Is visually guided reaching a myth?, Child Development, 1993)

Observations (3)

- The S-M learning is all relative - based on changes - no absolute values are needed

  A given reset location provides a reference that anchors the maps - (but this could be altered later).

The future…

Discovered structure

- Self movement - motor control, S-M coordination, spatial limits
- Object contact - static environment, spatial structure
- Loss of contact - dynamic environment.

S-M mappings

- Maps have many advantages - partial maps effective, gross to fine scale management, generalisation, cross-modal action.
- Also supports rehearsal, planning and imagined action.

Importance of constraints

- Scaffolding
- Bandwidth reduction
- Degrees of freedom reduction

Constraint lifting

- Main early learning mechanism
- Triggered by plateaus in activity
- Constraints used: tactile/vision/map scale.

Importance of Play

- Very prevalent in primates
- Role? - rehearsal, practice, exploration
- Exhaust plateaus before next stage?
- Test out all constraints?
- Growth of imagination.

Return to Issues

- Why development?
  - Behaviour based
  - Transitions between skill stages
- Why infants?
  - Stage n+1 argument
- Why robots?
  - Easiest way to embodiment

Summary - the important bits

- Behaviour-based
- Development is essential for learning
- Infancy is a very important developmental period
- Psychology is where the data can be found
- Simplicity of mechanisms
- Synthesis, test cycle
- “law of uphill analysis and downhill invention”
- Most of this is under-rated or under-investigated.