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# Number Understanding Modelling in a Behavioural Embodied Robotic System (NUMBERS)

# Outline of the presentation

- Background and motivation
- Models and Experiments
- Outlook of current work

# Embodied Cognition

- **The concept of embodied cognition affirms that the nature of intelligence is largely determined by the form of the body.**
- The embodied cognitive approach is the motivation behind a strongly humanoid design of the some of the recent and most advanced robotic platforms.

iCub

NAO

ASIMO

# Cognitive Developmental Robotics

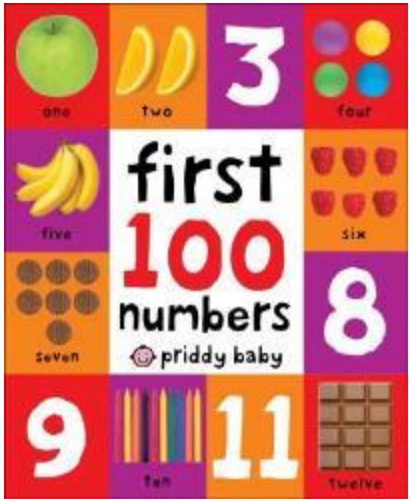
- Developing cognitive abilities like human children and babies
- Robots learns from interaction with the environment


In 1950, Alan Turing suggested:

*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.*

# Number cognition

- One of the distinctive components of human intelligence
  - essential for success in academic and work environments but also in practical situations of everyday life
- Observation of numerical practice can provide explanation of how the mind works

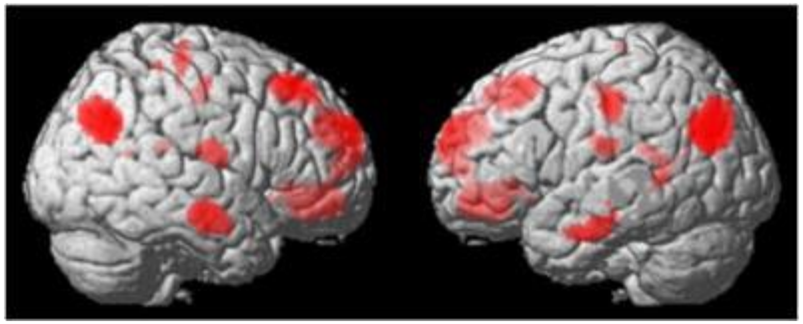



# Numbers and fingers

- Numbers are embodied and a special role is attributed to fingers.
  - We likely use a base 10 system because of the number of fingers in our hands
  - Finger are used for pointing, *montring* (i.e. represent numbers), counting, keep track when performing operations (e.g. additions).

# Neuroscientific evidence

- Fingers may have a role in setting up the biological neural networks for more advanced mathematical computations Moeller et al. (2011).
- Empirical studies suggest that there is ***a neural link or even a common substrate*** for the representation of numbers and fingers in the brain (Andres at al. 2012).
- Tschentscher et al. (2012) found fMRI-measured brain activation in adults when no motor response was required during the task, demonstrating a lasting neural impression.



# Developmental psychology evidence

- Domahs et al. (2008, 2010) observed children performed a disproportionate number of **split-five errors** in mental calculations and assumed this is related to five finger-counting system.
- This effect has been observed also in adults (Klein, et al., 2011), suggesting the lower level skills build the higher level cognition and the neural links can persist in adulthood.
- A recent study shows that combining finger training intervention to mathematical training can improve children quantitative skills (Jay & Betenson, 2017).

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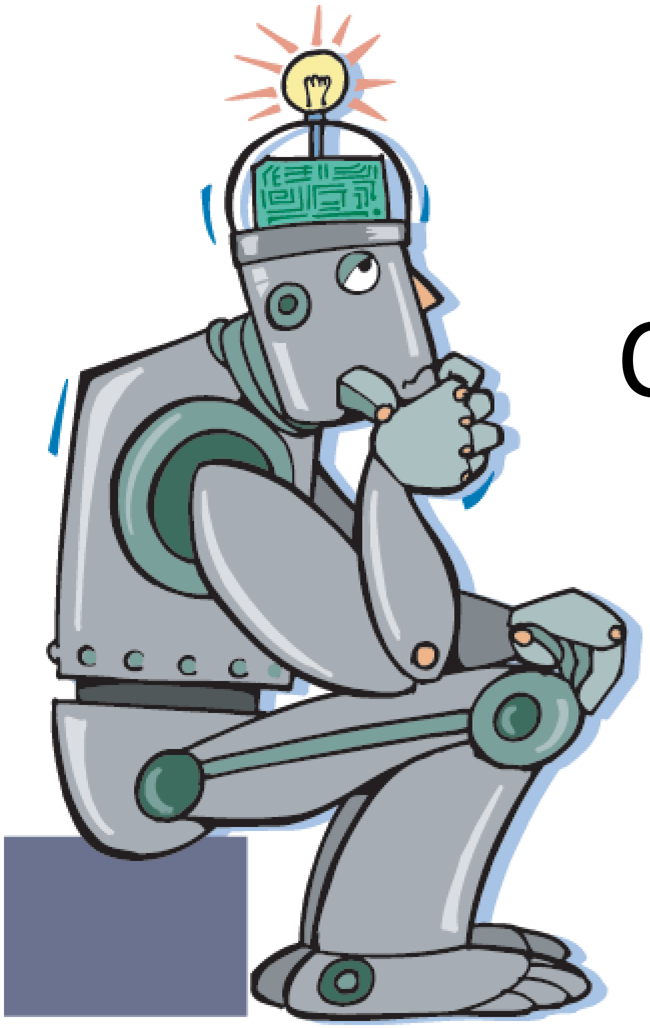
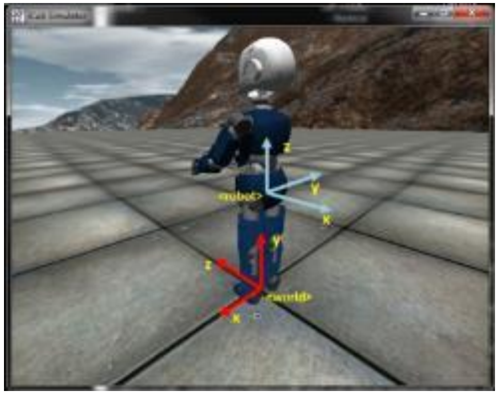


# Cognitive Models and Experiments

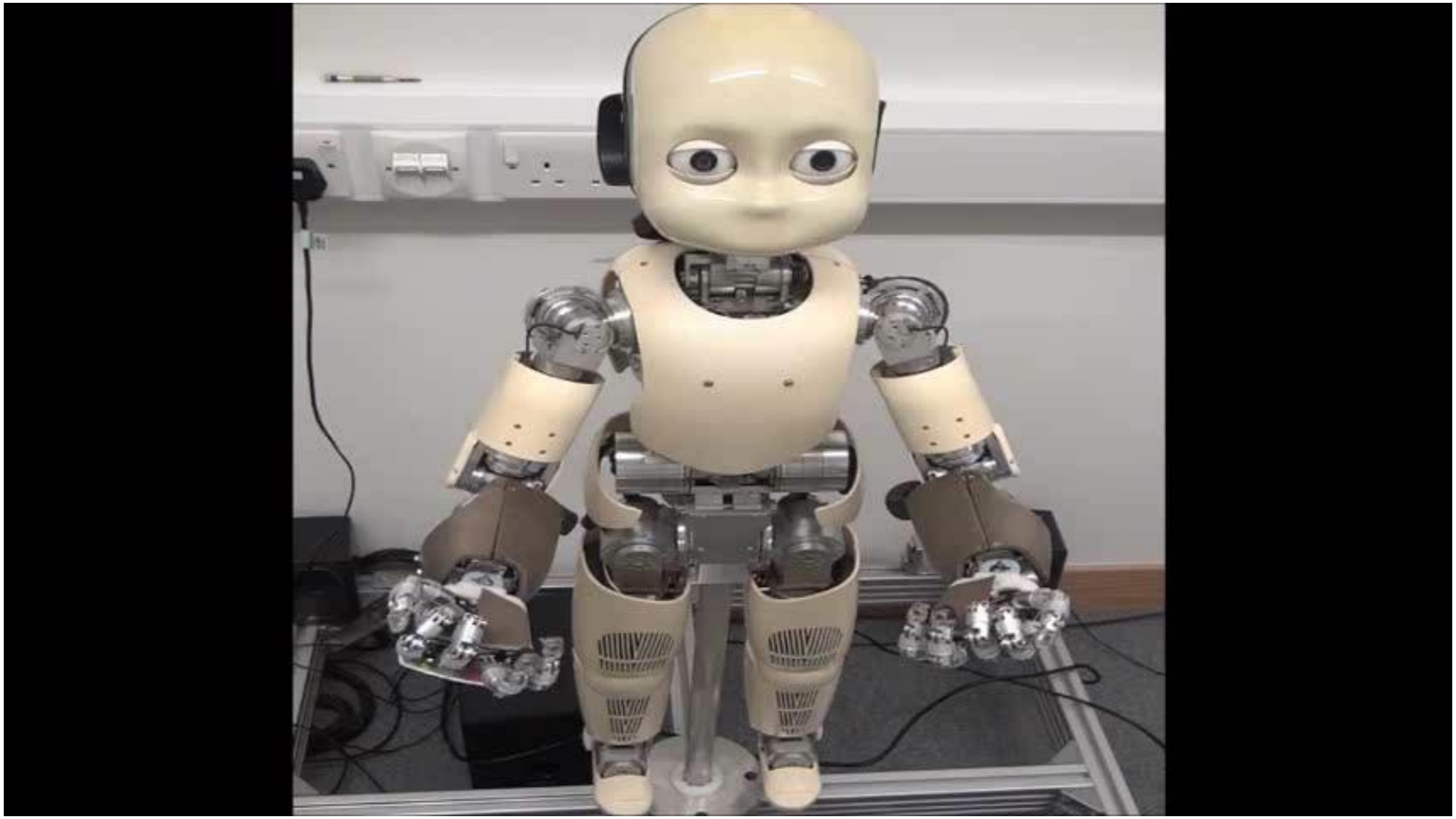
# The iCub robotic platform

The iCub platform is a child-like (3-4 years old) humanoid robot (approximately 1m tall), with 53 degrees of freedom distributed on the head, arms, hands and legs.

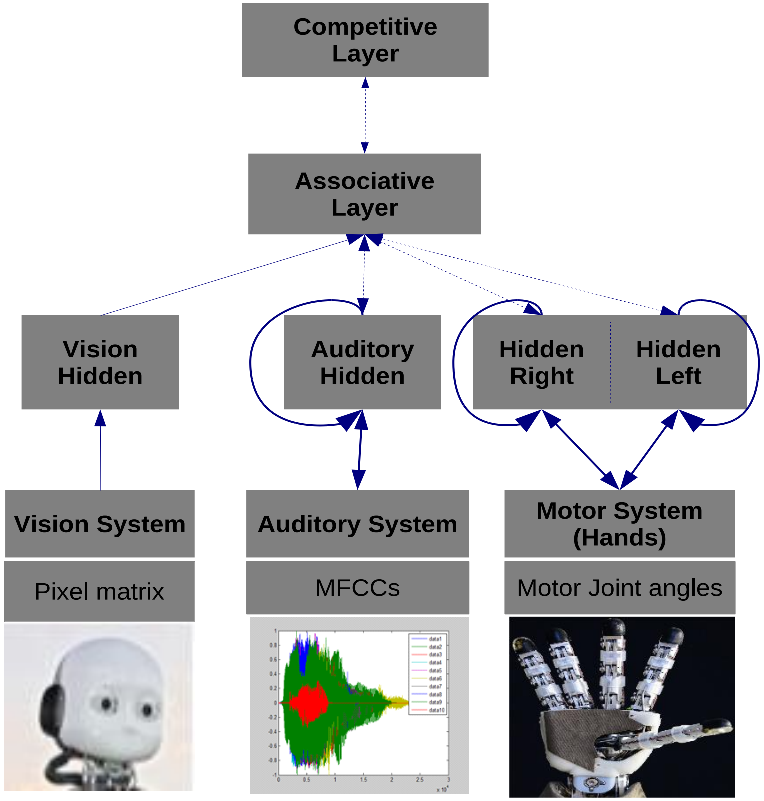
It can see and hear, it has the sense of proprioception (body configuration) and movement (using accelerometers and gyroscopes).



# iCub counts with its fingers



# Model of sequential learning



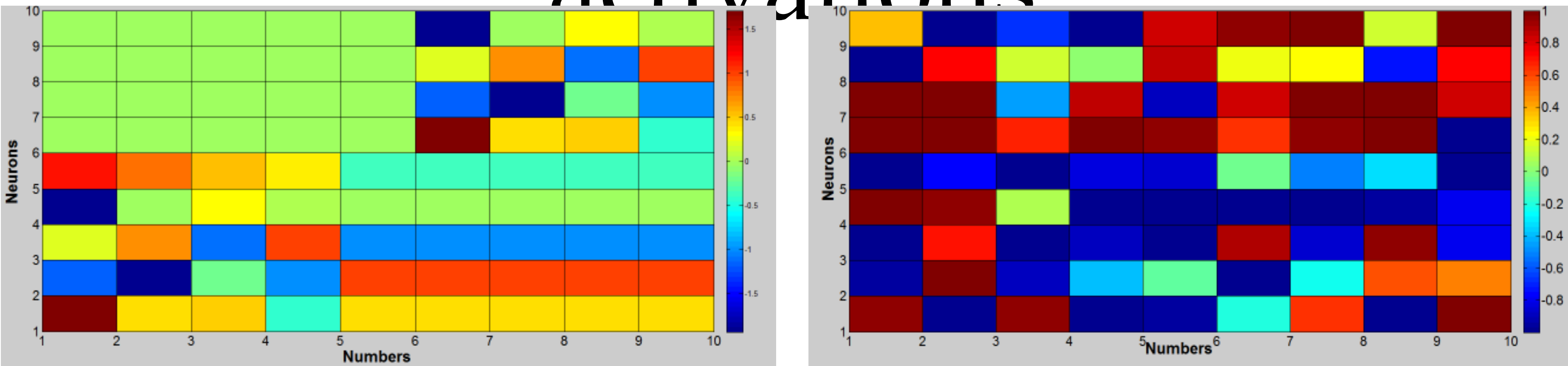

$$softmax(\mathbf{q}, i) = \frac{e^{q_i}}{\sum_{j=1}^{n} e^{q_j}}$$

Recurrent networks of the Elman type.

The competitive layer is trained to classify the inputs in ten classes (i.e. the numbers from 1 to 10) with a <u>likelihood</u> of the classification.

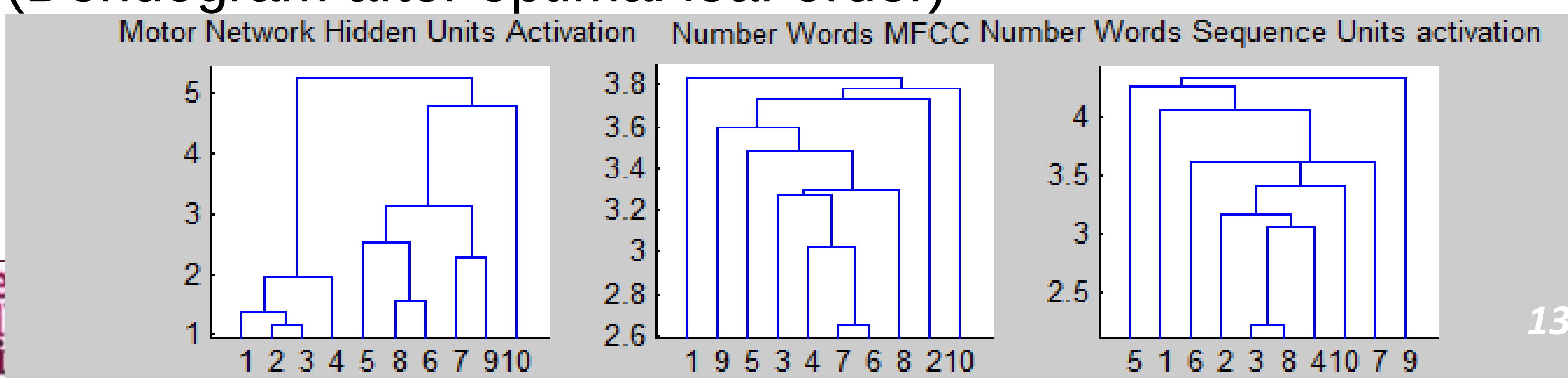
De La Cruz VM, **Di Nuovo A**, Di Nuovo S and Cangelosi A (2014). Making fingers and words count in a cognitive robot. FRONTIERS IN BEHAVIOURAL NEUROSCIENCE (1662-5153), 8:13.

# Analysis of hidden units activations

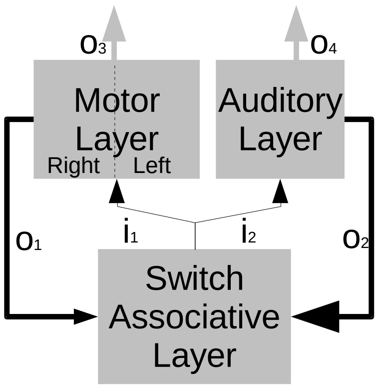


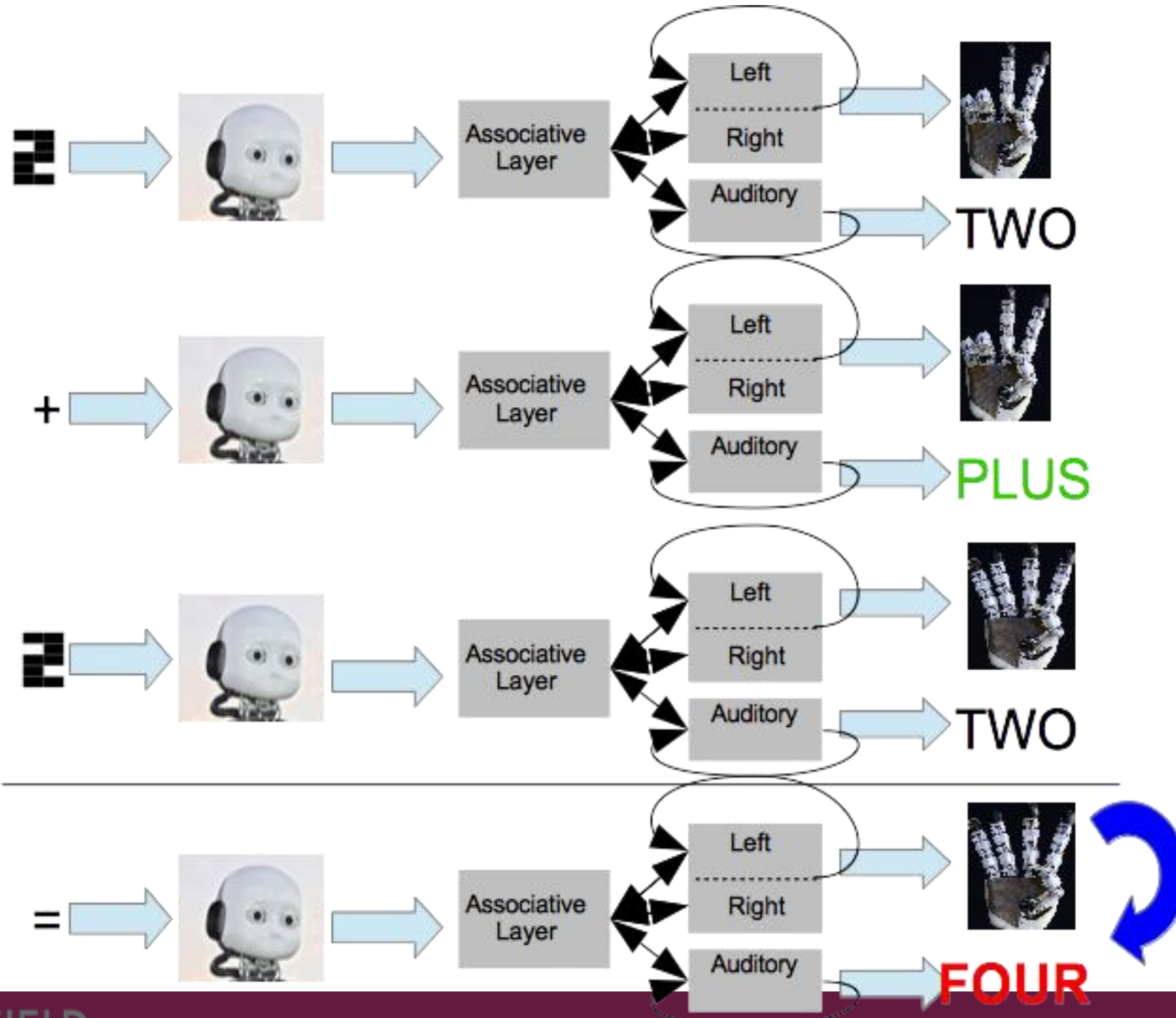

(a) Finger sequence     (b) Word sequence

- The model simulates lateralization when representing the numbers internally, as shown by Tschentscher et al. (2012) with fMRI. Also the motor representation is optimal. (Dendogram after optimal leaf order)



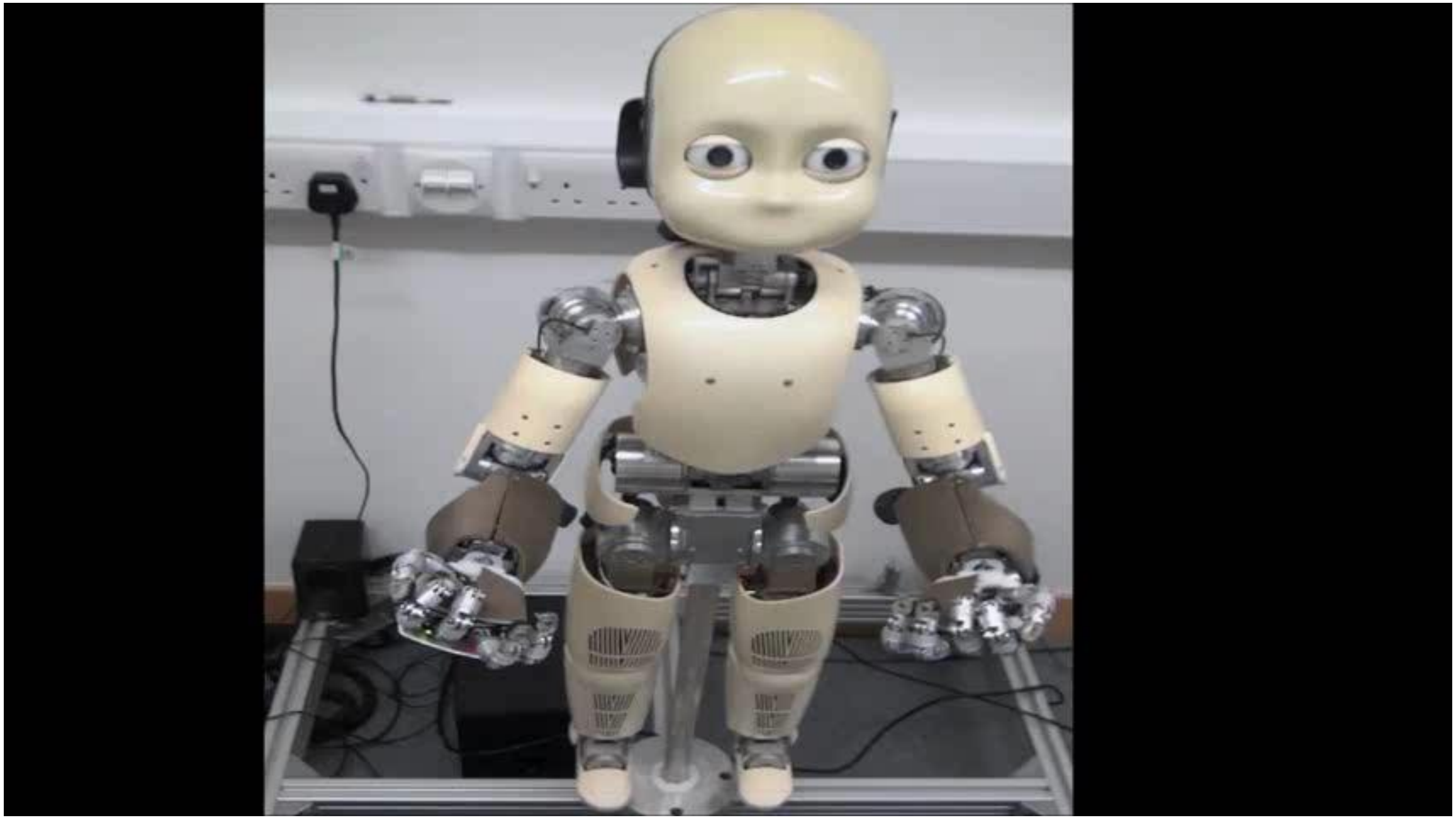
# iCub learns the sum



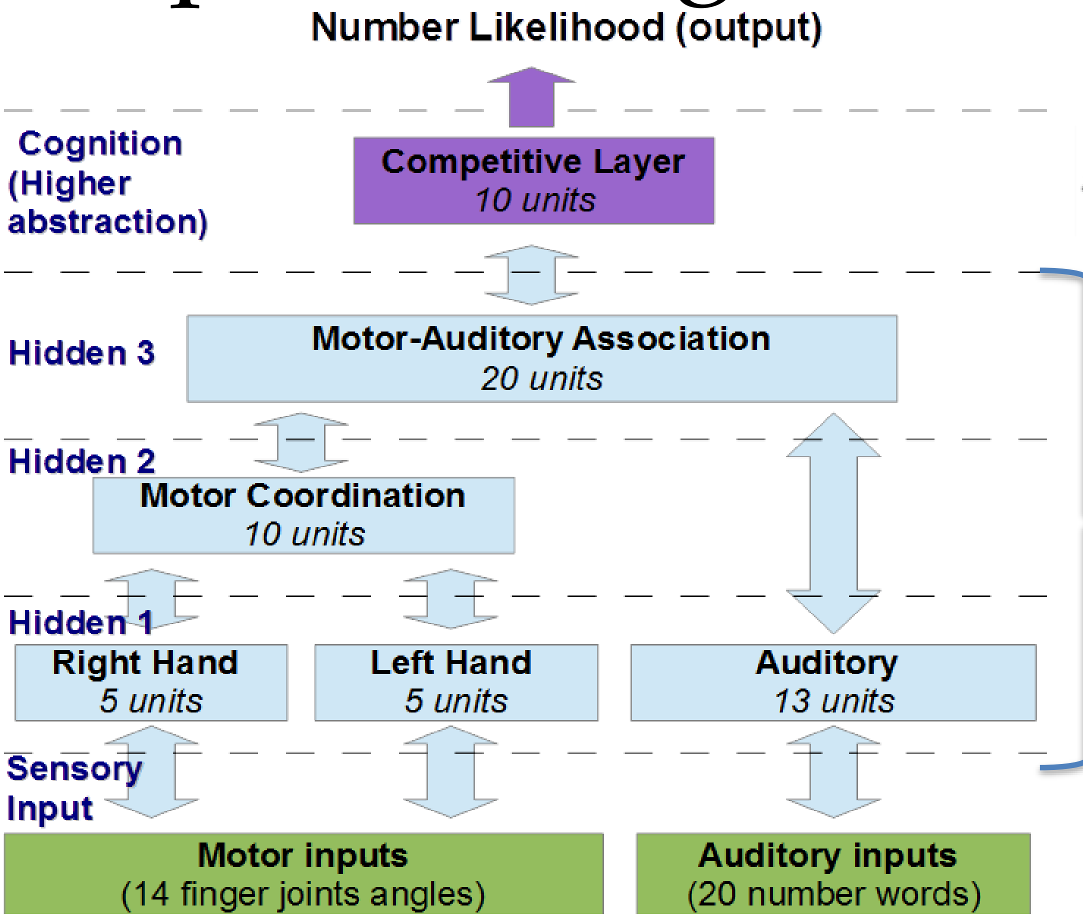




To perform the addition the robot uses the fingers as working memory, i.e. to keep track of the count.

# iCub perform 2+2

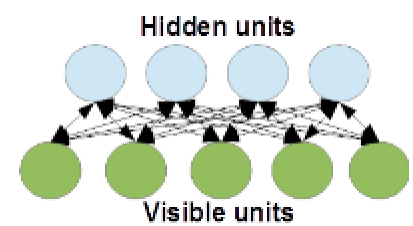


# Deep Learning Neural Network




$$softmax(\boldsymbol{q}, i) = \frac{e^{q_i}}{\sum_{j=1}^{n} e^{q_j}}$$

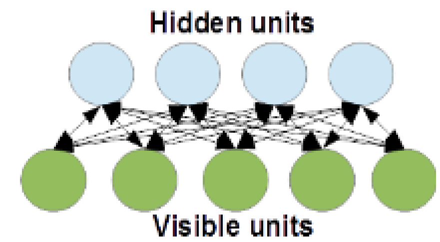
$$logsig(x) = \frac{1}{1+e^{-x}}$$

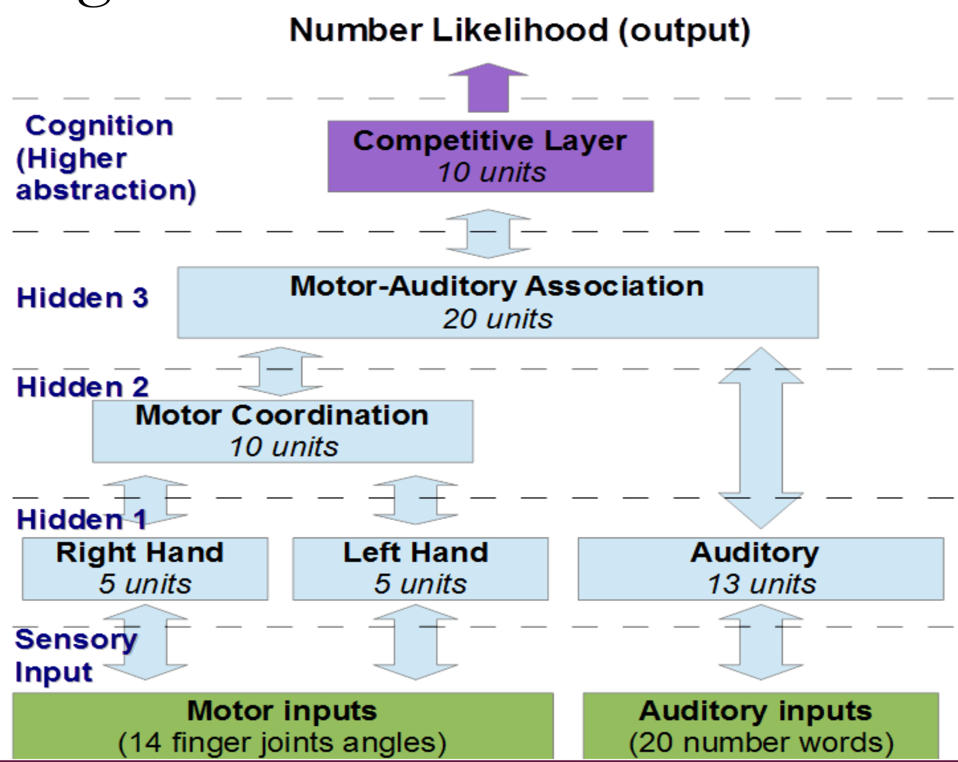



**Di Nuovo A.,** De La Cruz V.M. , Cangelosi A (2015) A Deep Learning Neural Network for Number Cognition: a bi-cultural study with the iCub. IEEE ICDL-Epirob 2015, 320-325.

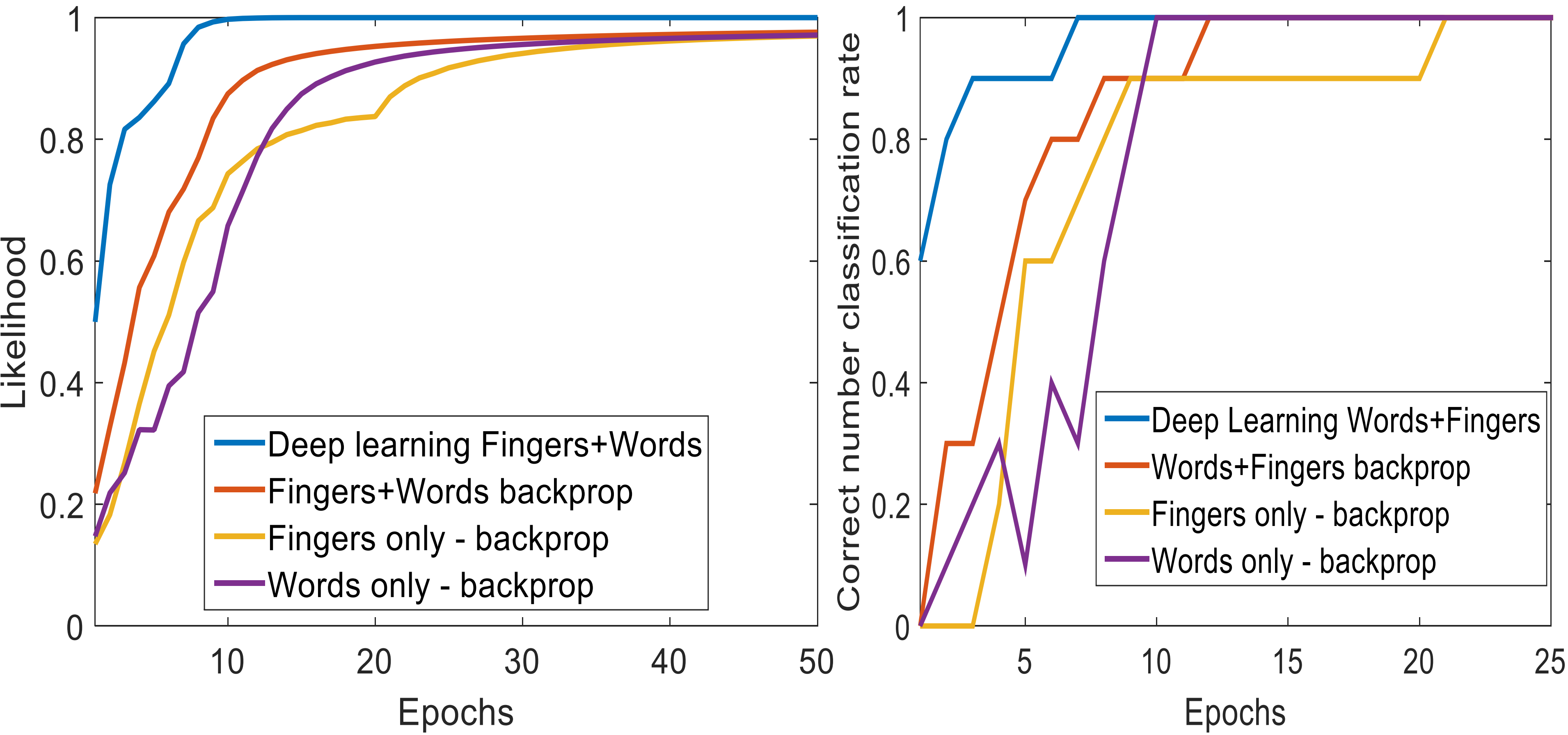
# Deep Learning with Fine Tuning

- Pre-training phase
  - Contrastive Divergence Algorithm (Hinton, 2006)
  - Unsupervised Training layer-by-layer
- Refinement phase
  - Backpropagation (Levenberg-Marquardt)



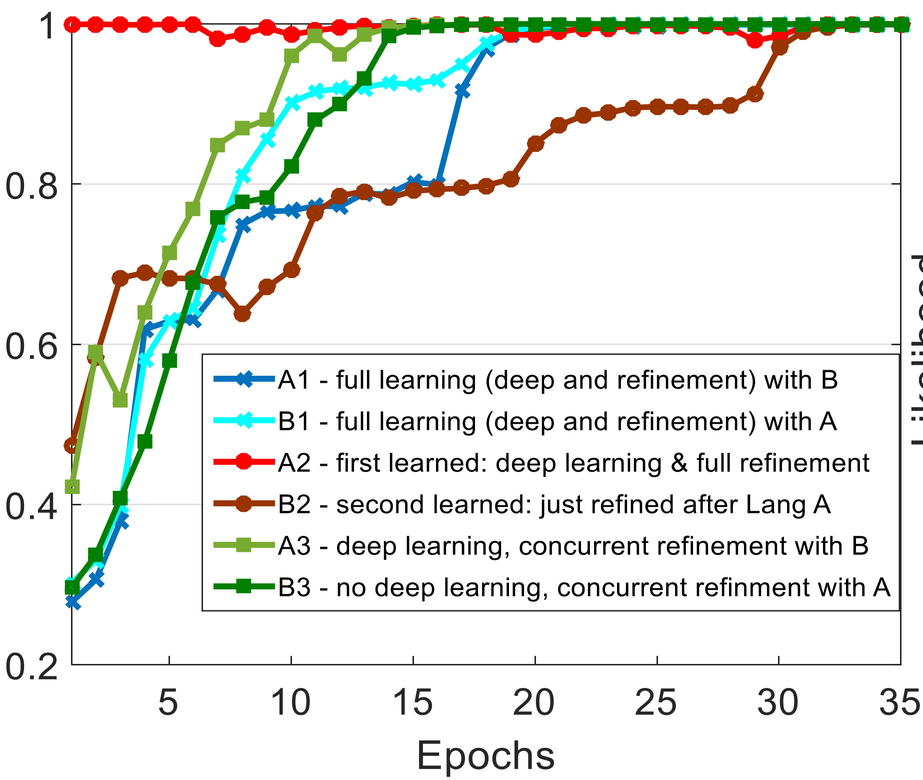
# Model validation



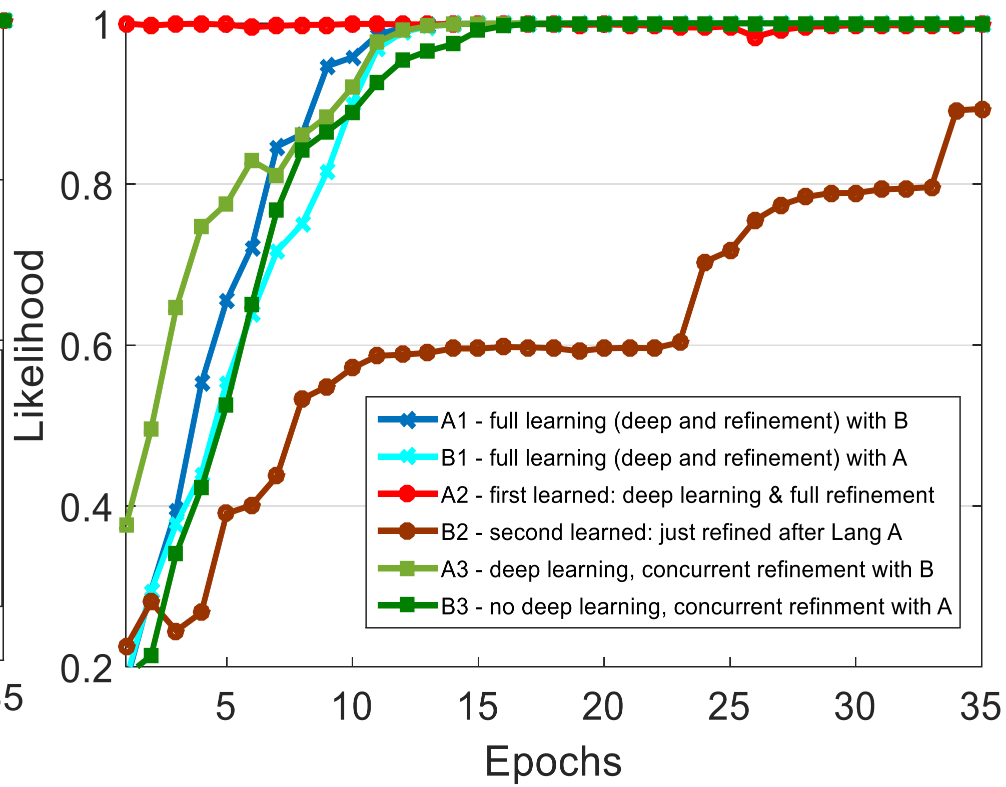
# Bi-cultural study

**2 cultures: A, B – 3 different conditions**

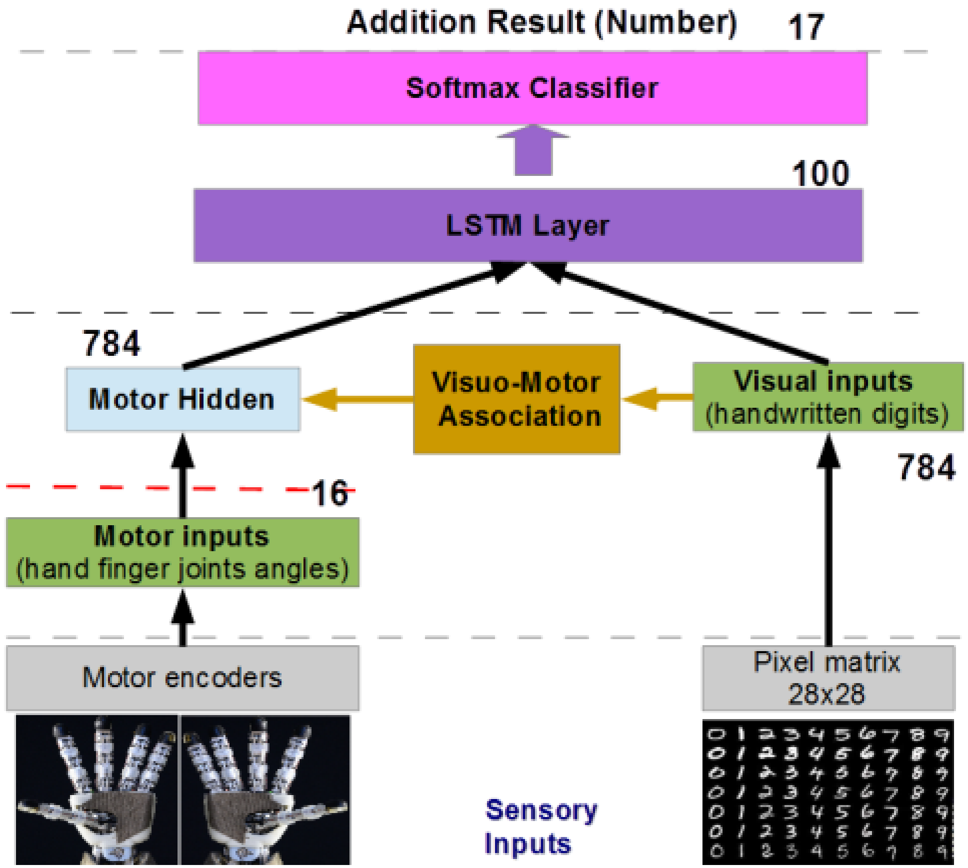
- Same counting strategy




- Different counting strategy



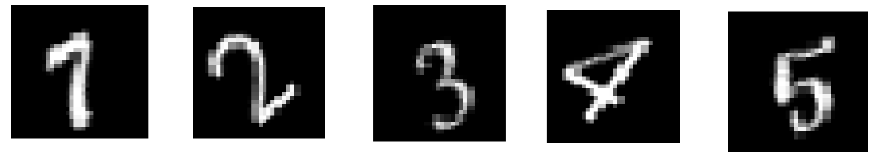
# Updated model with LSTM




**Di Nuovo, A.** (2018). Long-short term memory networks for modelling embodied mathematical cognition in robots. Proc. of the International Joint Conference on Neural Networks (IJCNN 2018), pp.1-7.

# Data sets

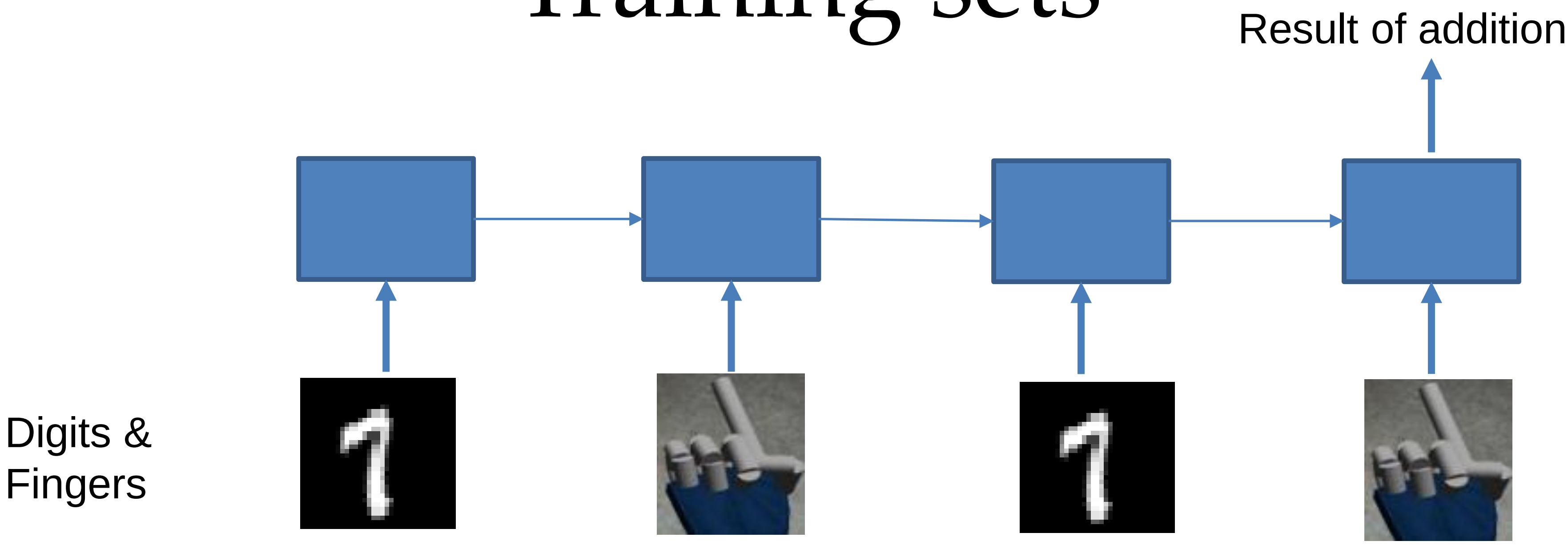
**Handwritten digits (MNIST database 1-9)**



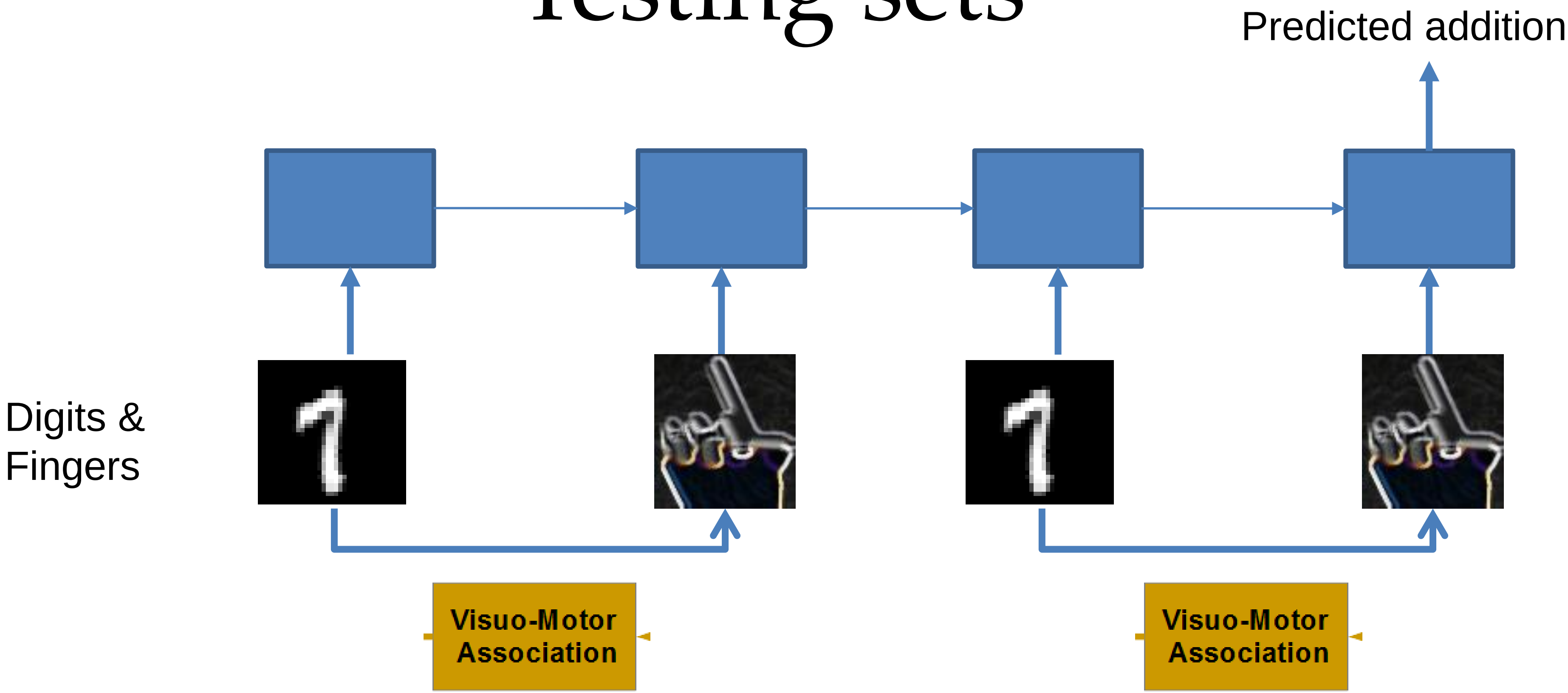
**Robot Hands Joints Encoders (16 DOF) American Sign Language**

- The task is the addition of two digits (from 1 to 9) in any order, e.g. 1+3 and 3+1 are different sets of inputs: a total of 81 combinations.
- The MNIST database has been reduced removing the zero: 54,077 training set and 9,020 for the test set.
- Training additions includes 81,000 sequences: 1,000 pairs of examples for each combination from the MNIST training set.
- Testing dataset is composed of 52,650 sequences, 650 examples from the MNIST testing set.

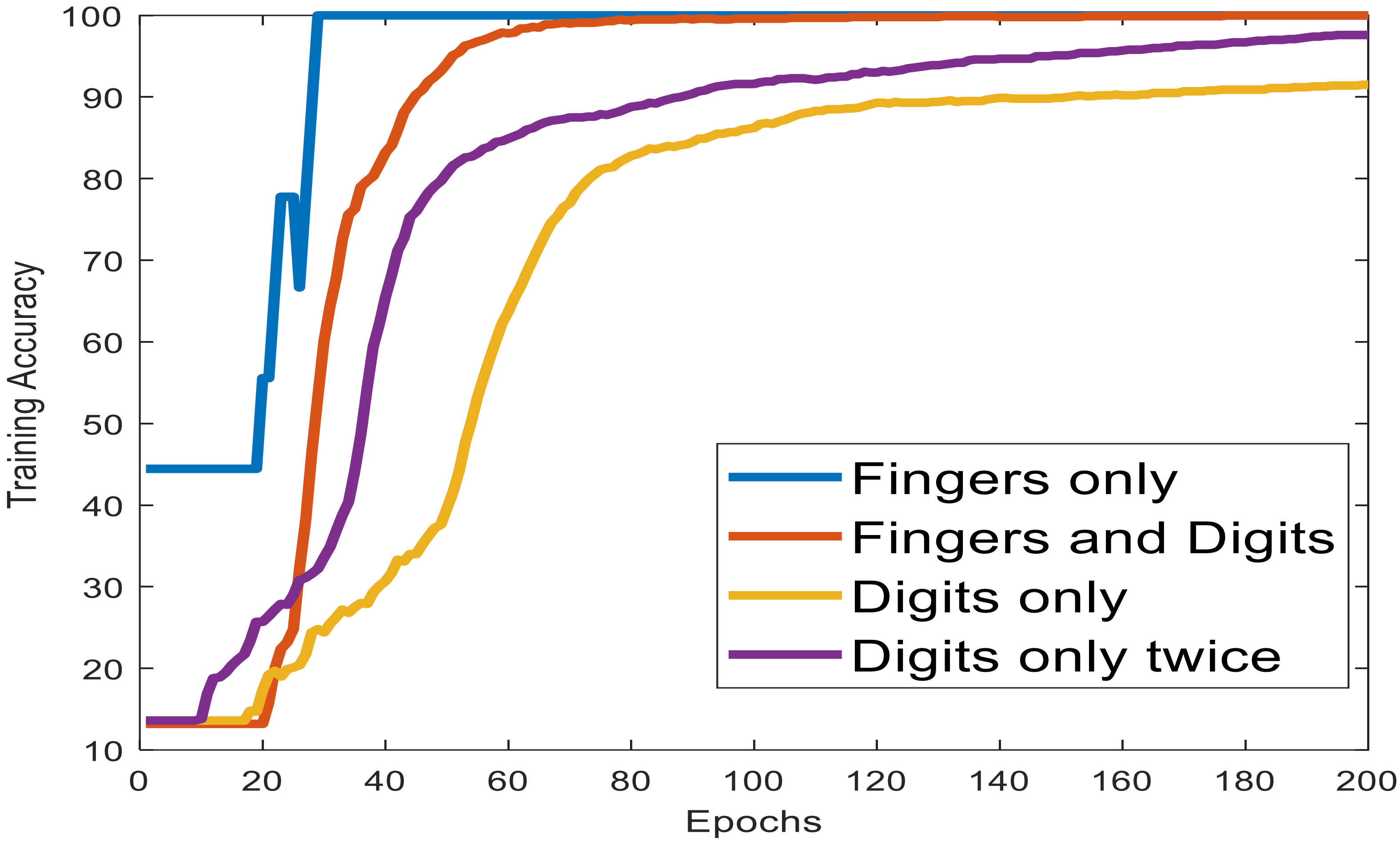
# Training sets



# Testing sets



# Training accuracy

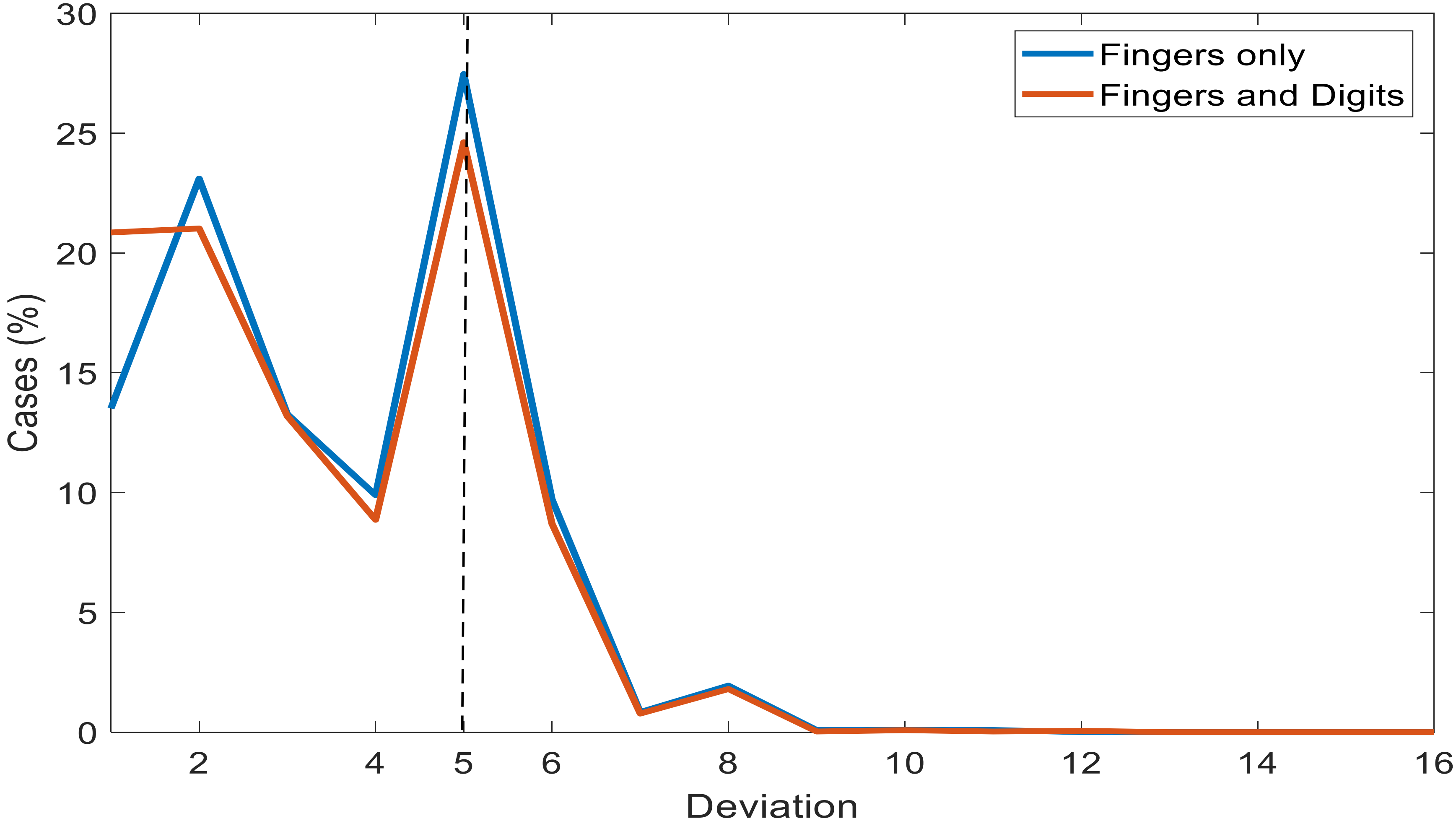


# Classification Rate and Mean Deviation

- Correct Classification Rate
- Mean Deviation from the correct result on the Testing Dataset

| Learning Approach | Correct Rate % | Mean Deviation |
|---|---|---|
| Fingers Only | 93.64 | 0.228 |
| Fingers and Digits | 93.14 | 0.230 |
| Digits only | 86.44 | 0.428 |
| Digits only (twice) | 90.34 | 0.316 |

# Absolute deviation from the correct addition (split-N)

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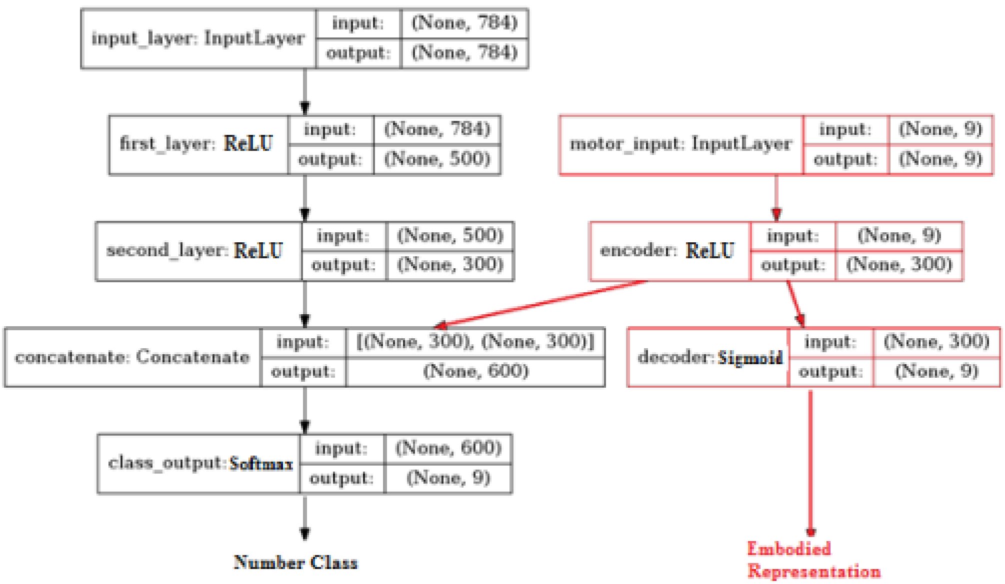
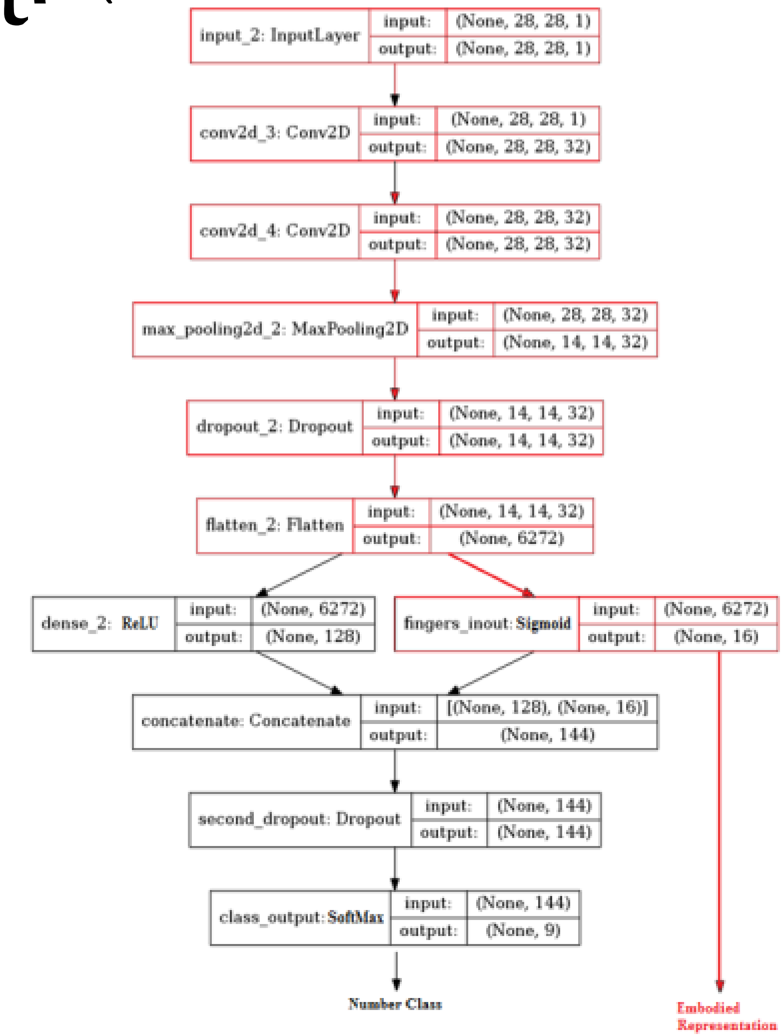
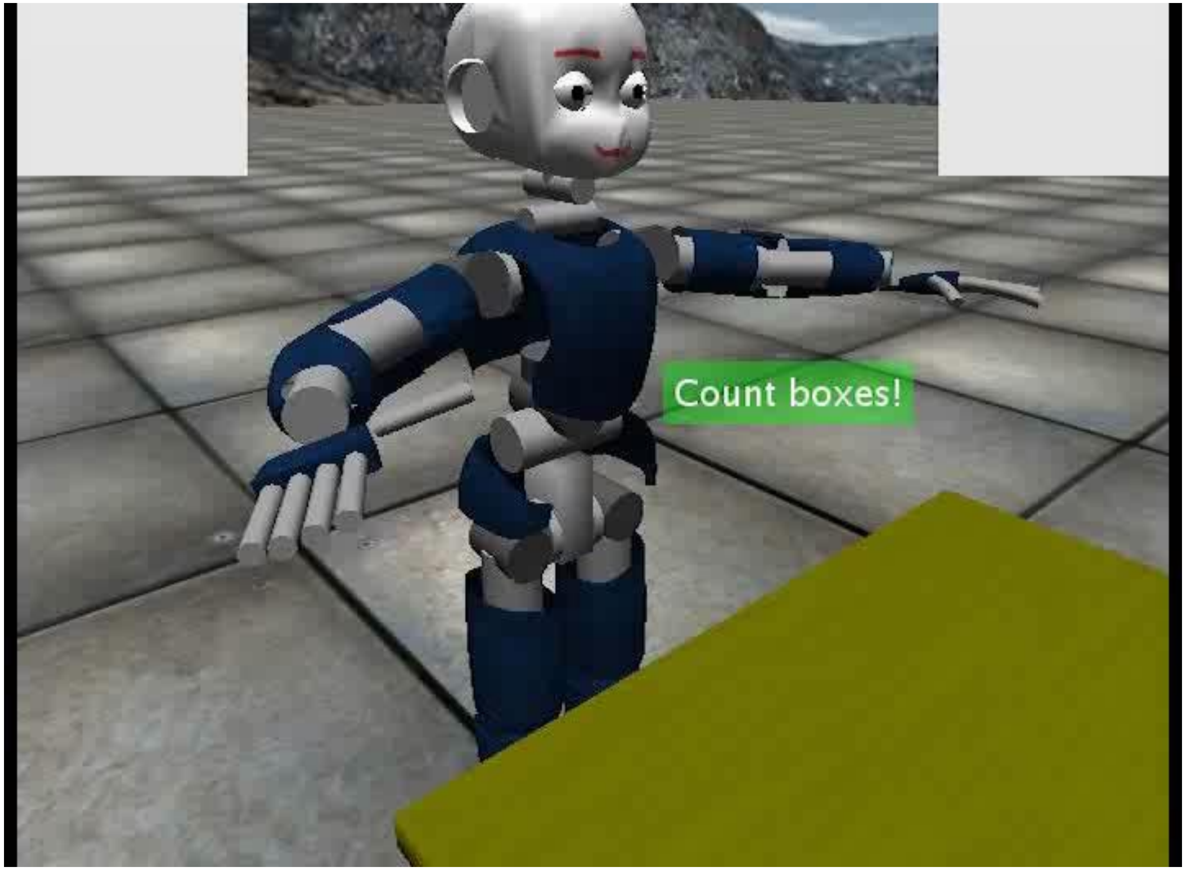
# Outlook of the current work

# neural link or common substrate?

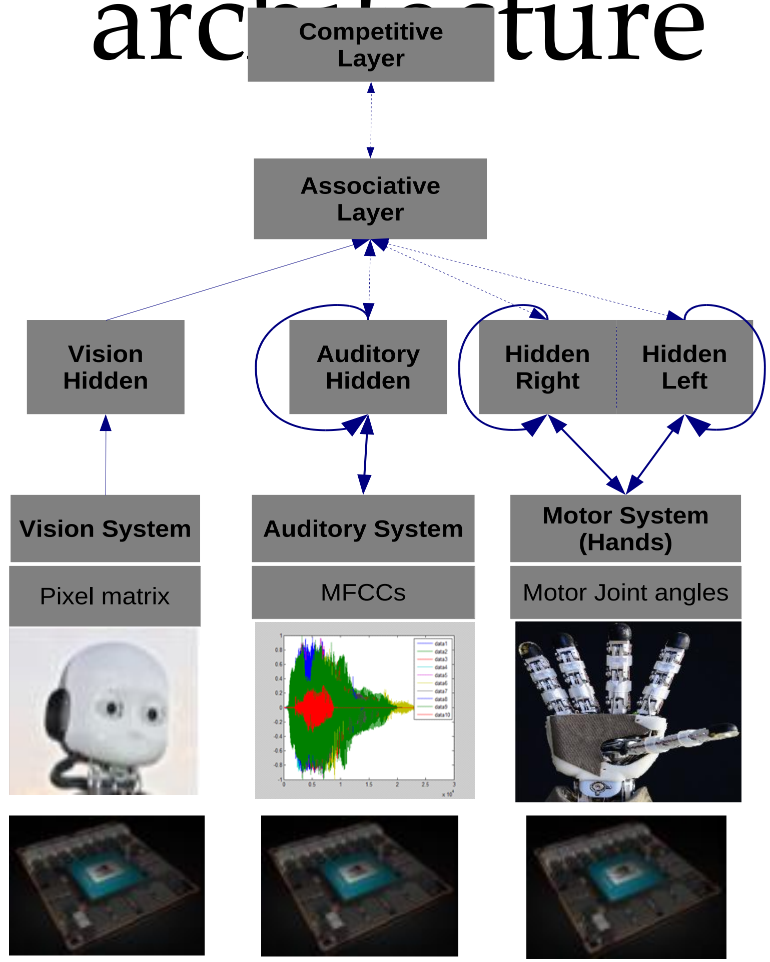


# Manipulation



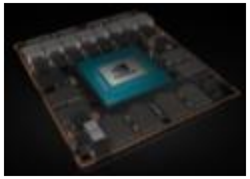
# Modular distributed architecture




video processing

audio processing

motor controller

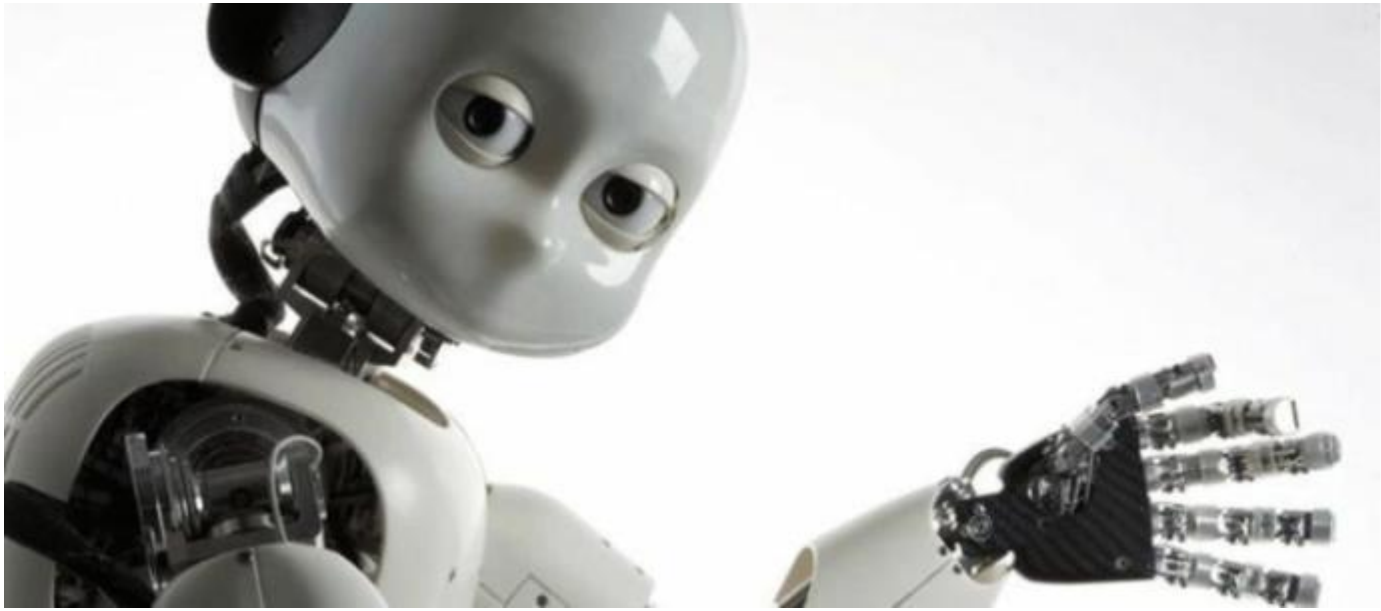


number cognition

# Application in children education

- Educational robots are "engaging, motivating, encouraging imagination and innovation, and may improve literacy and creativity, especially for children" (Cheng and Wang, 2011)
- Robots that can simulate learning basic mathematics can help children to learn via imitation and guided play.

# Thank you for you attention!

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