The Emergence of Grammatical Constructions: Insight from Neural Network Simulation, Neurophysiology and Robotics

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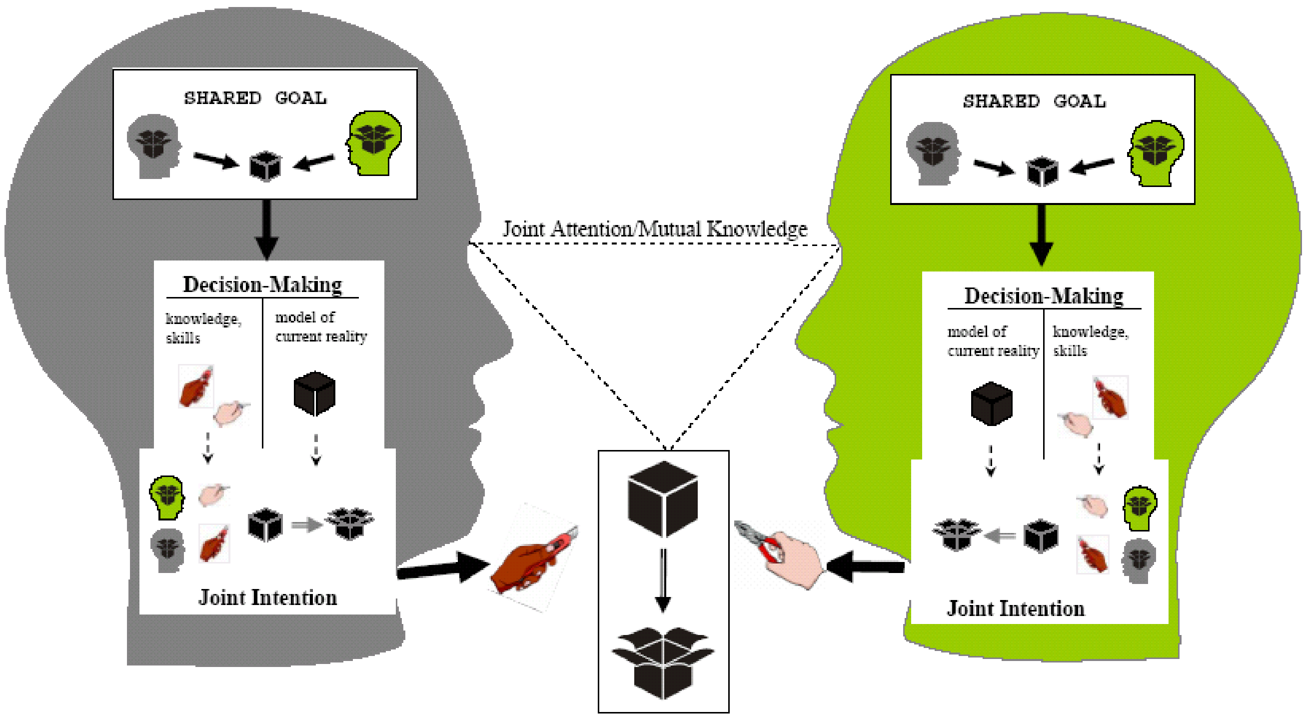
Outline

- Requirements on language: what is it for?
- What strategies can be employed?
- How can this be realized in neurophysiology?
- Testing the model?
  - Brain imagery
  - Simulation
    - Cross lingustic learning – English, French, Japanese
    - Insights into holophrase – abstract construction transition
  - Robotics
    - Learning from real data
    - Human Robot Cooperation
- Ongoing research

What is language for?
Sharing Mental States



Tomasello M, Carpenter M, Call J, Behne T, Moll HY (2005) **Understanding and sharing intentions: The origins of cultural cognition**, Beh. Brain Sc;. 28; 675-735.

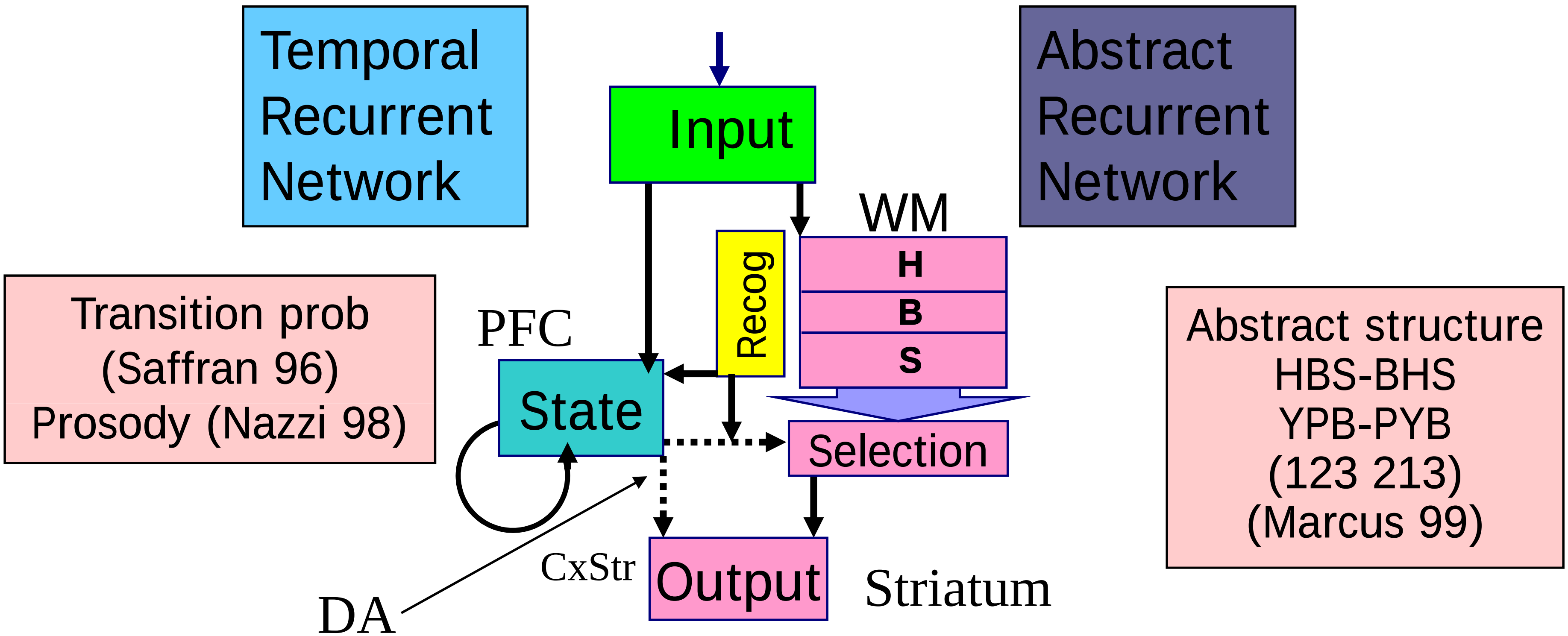
Requires a linearization of complex multidimensional representations

What encoding strategies can be employed?

- In the morphosyntactic arena, there is an item-based competition between *word orders* and *grammatical markings* centered on valence relations.
- At the core of syntactic processing is the learning and use of *item-based constructions*
  - children first learn that a verb like *throw* takes three arguments (thrower, object thrown, recipient)
  - by comparing groups of these item-based patterns through analogy, *children can then extract broader class-based patterns*

Competition Model - MacWhinney 2004, Bates & MacWhinney 1987
Usage Based Learning – Tomasello 2003
Construction Grammar – Goldberg 1999

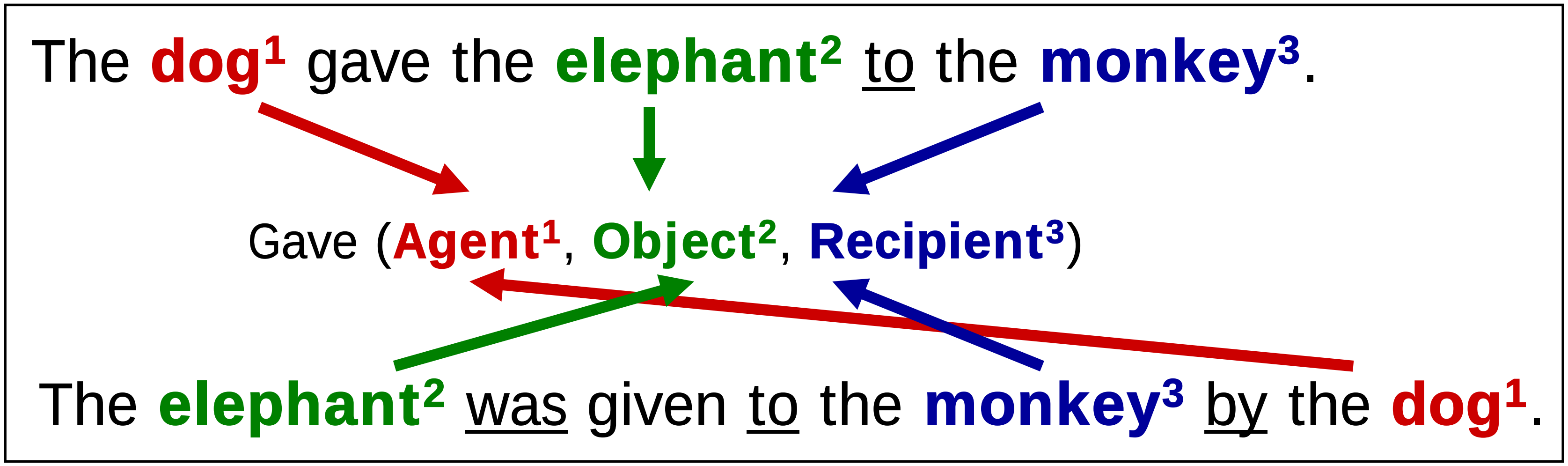
What could be the underlying neurophysiology?



Dominey, P. F., & Ramus, F. (2000). Neural network processing of natural language: I. Sensitivity to serial, temporal and abstract structure of language in the infant. *Language and Cognitive Processes, 15*(1), 87–127.

(Dominey et al. J Cognitive Neuroscience 1995, 1998)

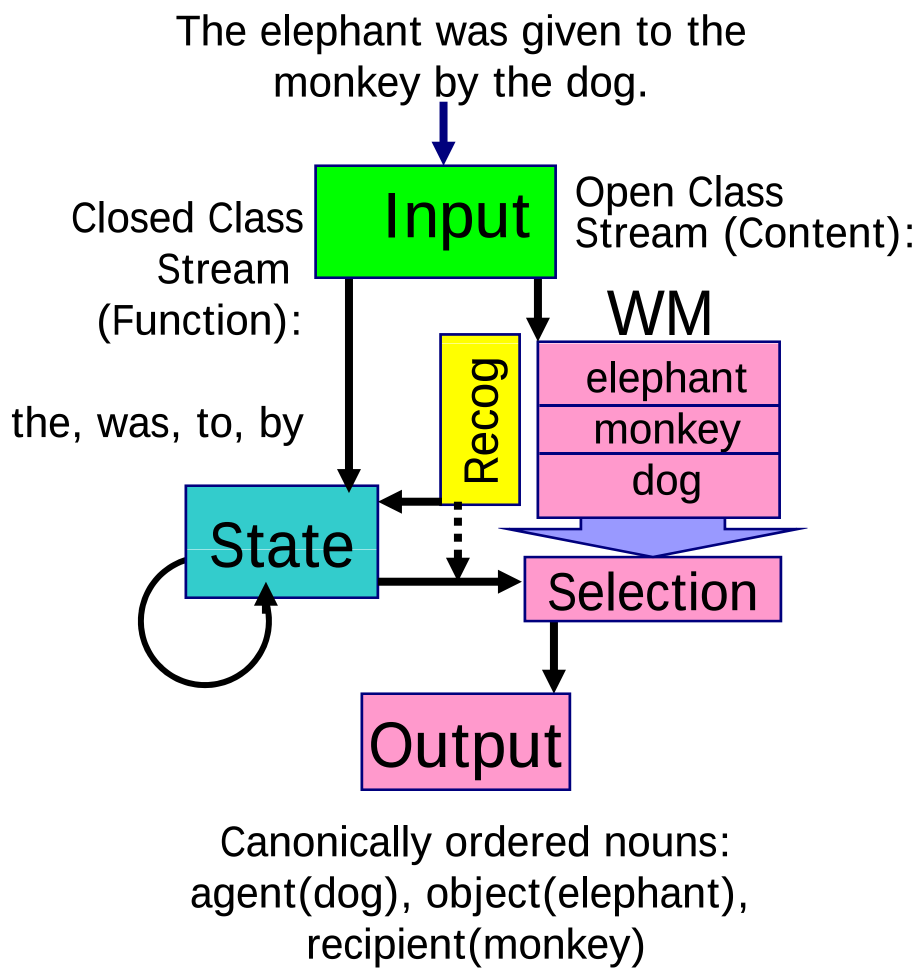
Extension of Abstract Structure to Grammatical Constructions



- Different surface forms map to same meaning
- Indicated by function words (was, to, by)

- Non-Linguistic correlate – "equivalence hypothesis"
  - 123X123, 231Y123

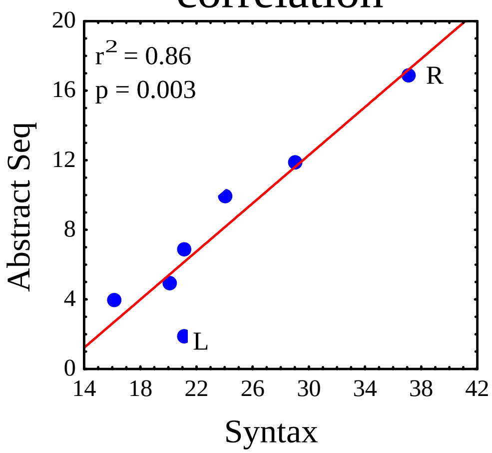
Abstract sequencing model learns grammatical constructions



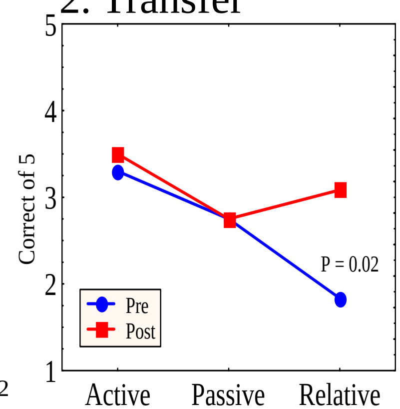
Dominey et al (2003) Brain and Language

Validating the 'Equivalence Hypothesis'

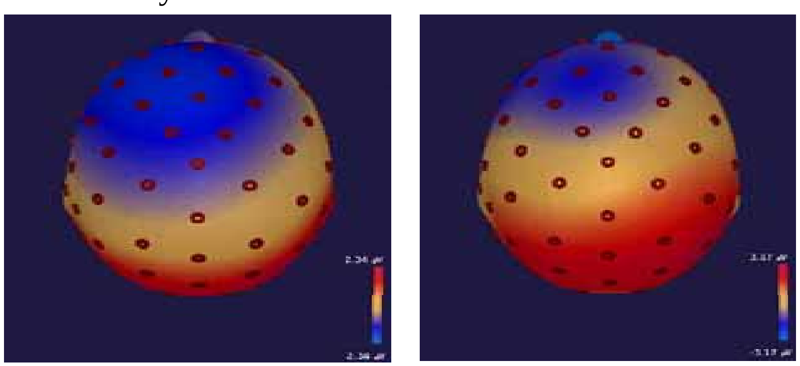
1.Agrammatic correlation



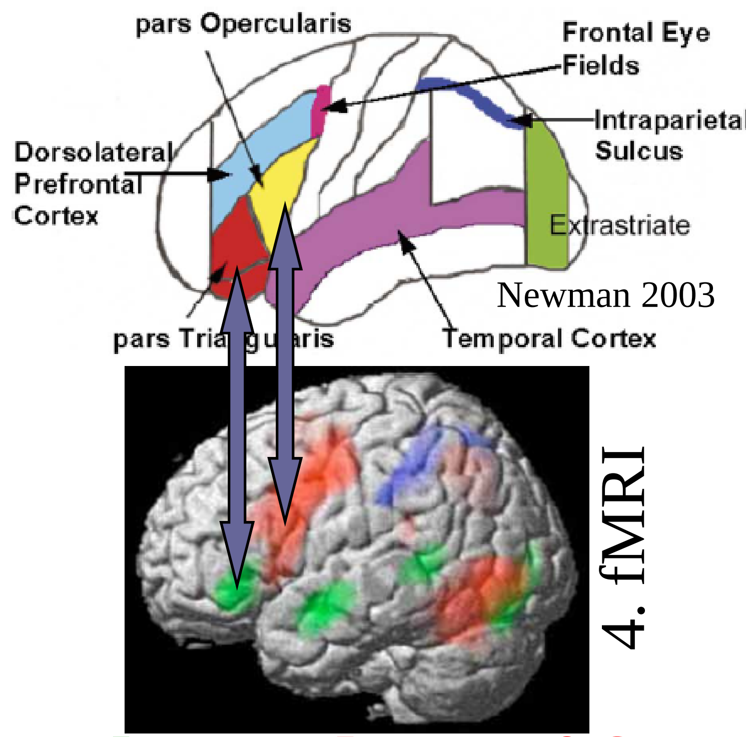
2. Transfer



3. ERP



Language Sequences



4. fMRI

Language **Language & Seq**

4. Hoen, Dominey et al Cortex 2006

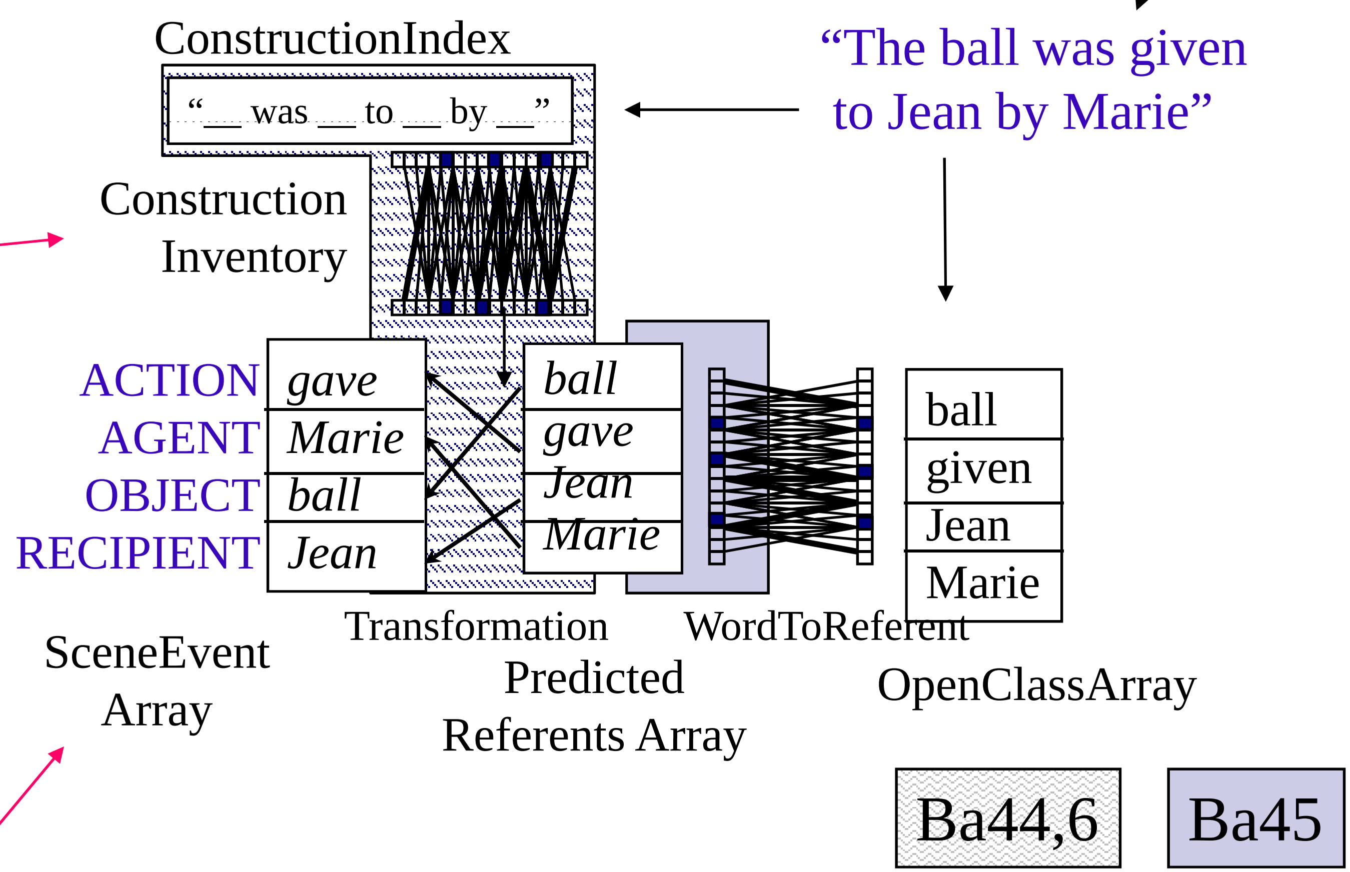
1. Dominey et al B&L 2003, 2. Hoen, Dominey et al. NeuroReport 2003, 3. Hoen & Dominey NeuroReport 2003

A Neurolinguistic Model of Grammatical Construction Processing

Inventoried via
competing cues In a Recurrent Cortical Network

form

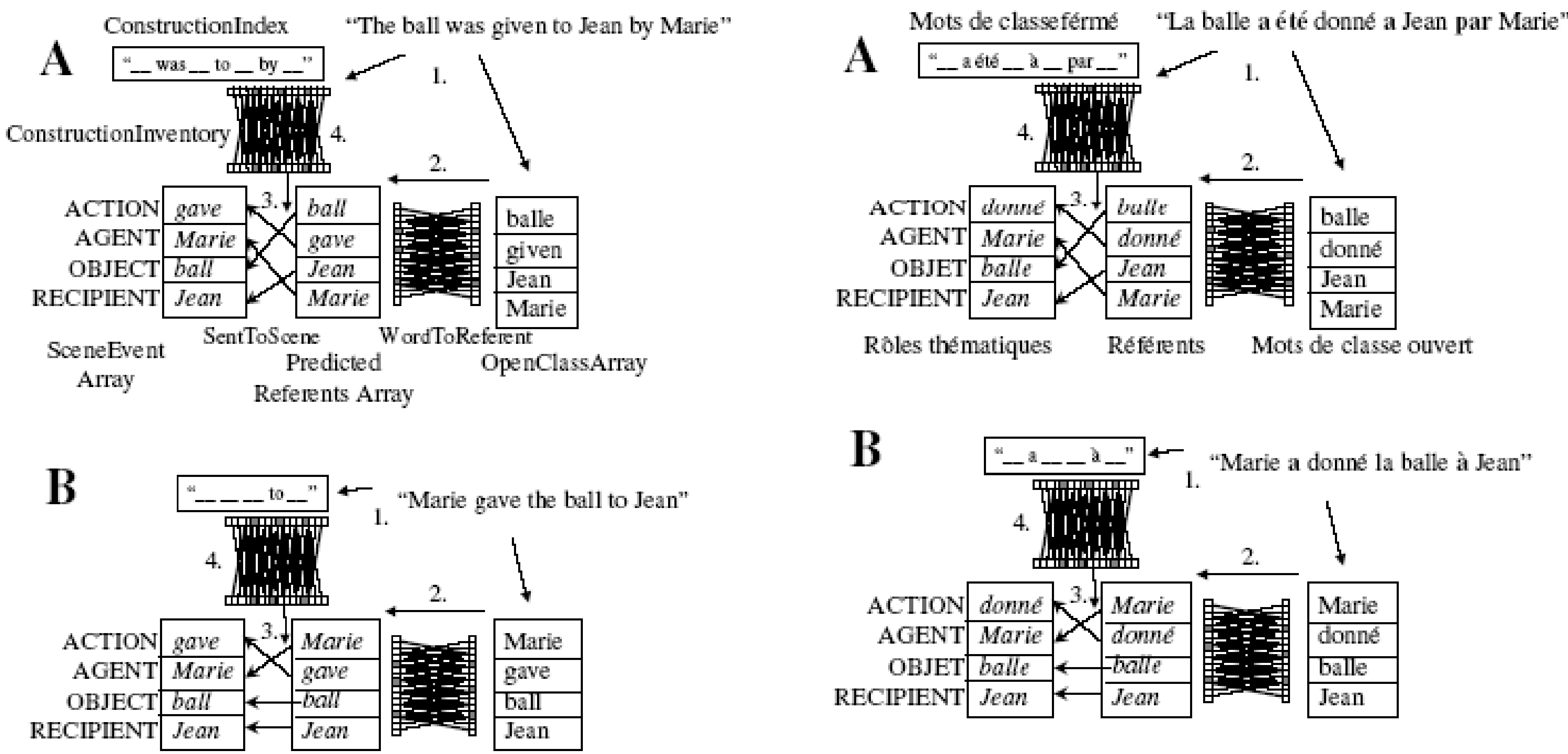
Structured inventory of form to meaning mappings: Cx-Striatum Assoc Mem



meaning

(Dominey, Hoen, Inui 2006 J Cog Neuroscience)

Grammatical Construction Model



Cross-Linguistic Validation: Japanese

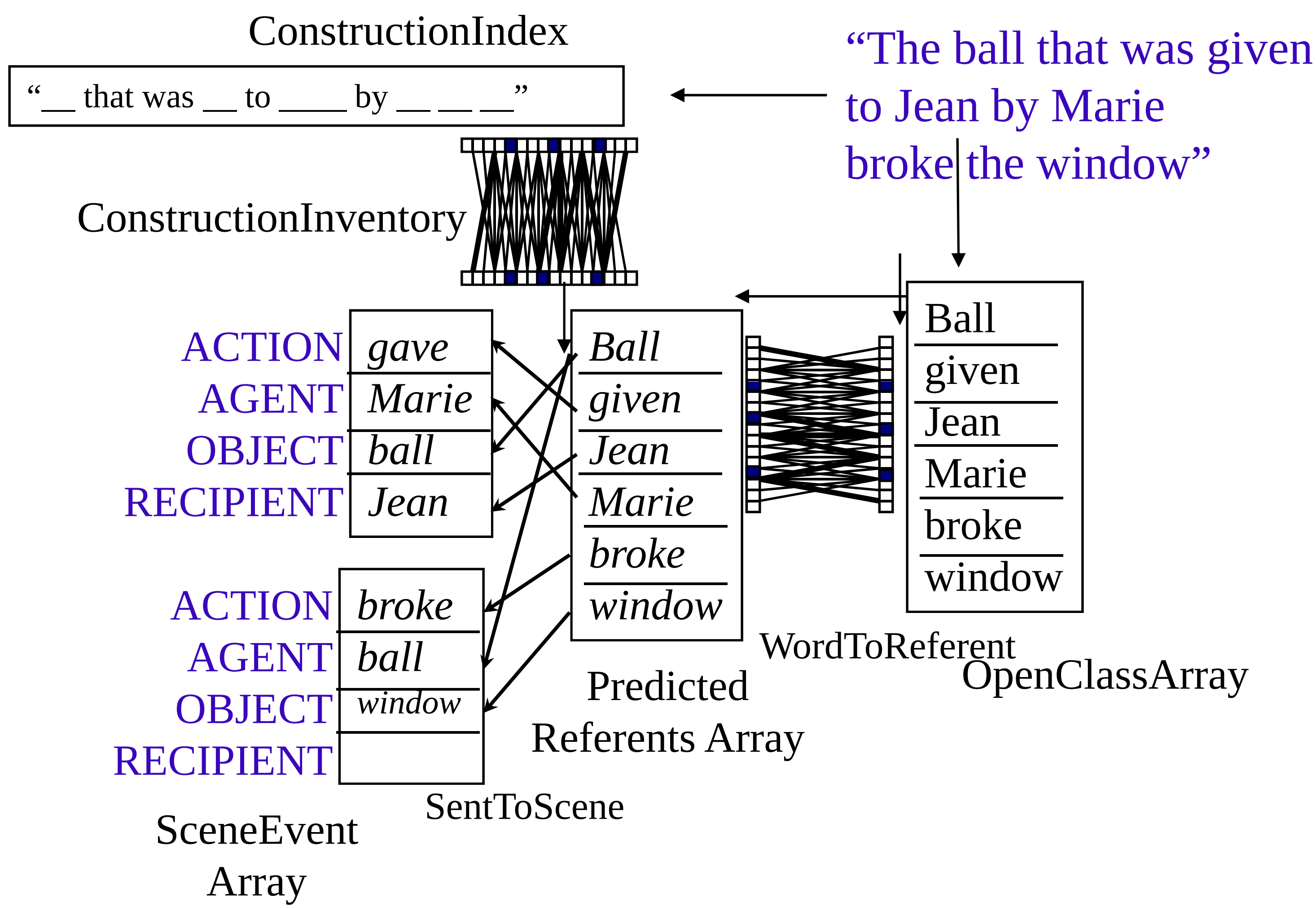
Block-ga circle-wo oshita triangle-ni-yotte tatakareta.
Circle-wo oshita triangle-ni-yotte block-ga tatakareta.
The block was hit by the triangle that pushed the circle.
Pushed(triangle, circle), Hit(triangle, block)

Circle-wo tataita block-ga triangle-ni-yotte osareta.
Triangle-ni-yotte circle-wo tataita block-ga osareta.
The block that hit the circle was pushed by the triangle.
Hit(block, circle), Pushed(triangle, block)

Block-ga circle-wo oshita triangle-wo tataita.
Circle-wo oshita triangle-wo block-ga tataita.
The block hit the triangle that pushed the circle.
Pushed(triangle, circle), Hit(block, triangle)

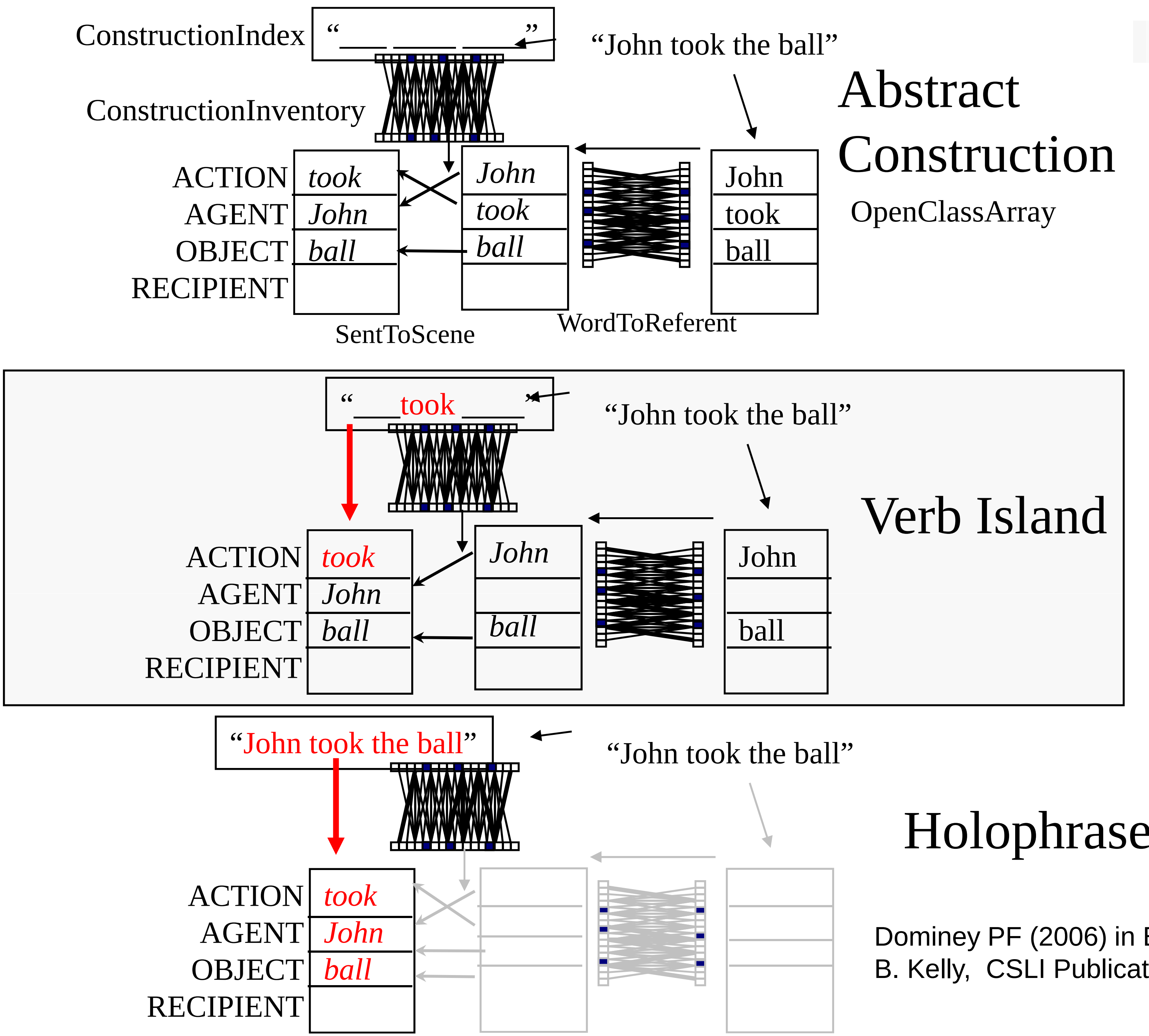
N = 26 constructions
Dominey & Inui CoLing 2004

Conceptual and Phrasal Complexity



Problem: From Holistic to Abstract Constructions

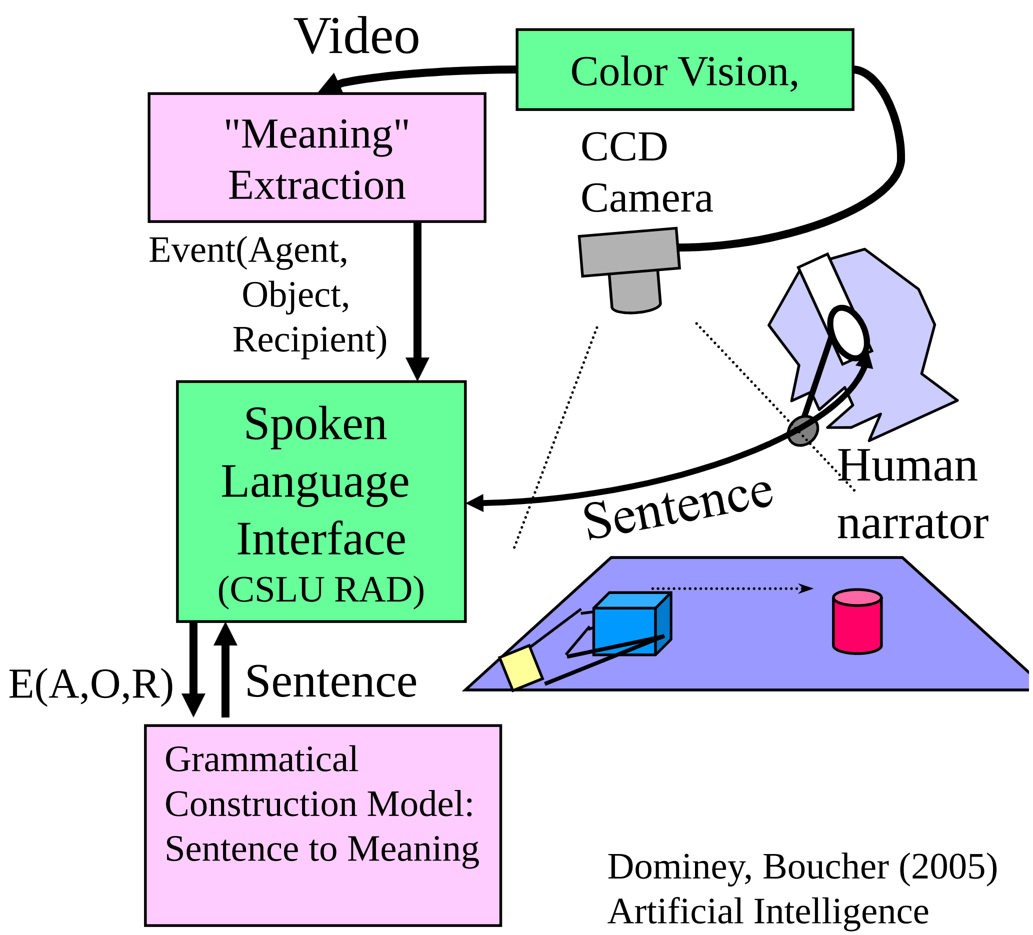
- Holophrases
  - « Gimme the ball »
  - lexical chunk mapped to meaning
- Argument constructions (pivot, island, ..)
  - fractionation/liberation of lexical elements
  - fractionation of semantic representations (e.g. Agent or Patient of an action)
  - progressively abstract form-to-meaning mapping



Dominey PF (2006) in Eve Clark and B. Kelly, CSLI Publications, Stanford

Embodied Language Learning: Human Teaches Robot

- "Perceptual Processing"
  - Color based segmentation
  - Speech recognition, syntheses, dialog mgmt (CSLU RAD)
- "Cognitive Processing"
  - Extraction of "Meaning" : Action Perception
    - Events from spatiotemporal schemas
  - Sentence-Meaning mapping
    - Grammatical Constructions

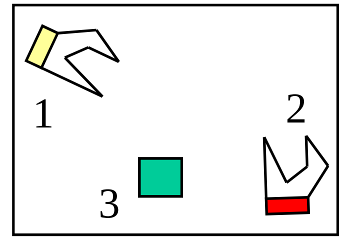


Dominey, Boucher (2005) Artificial Intelligence

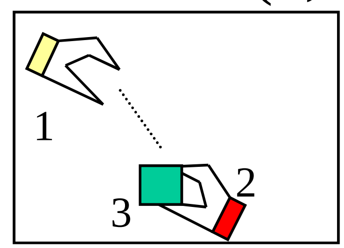
Action Perception: Extracting meaning from vision

- Events categorized in terms of perceputal primitive “contact”
  - *contact(agent, objet, duration)*
  - *Position,velocity*
- Single-contact events
  - *touch, push, take* can be described as contacts, and durations.
  - duration: *Touch* < *Push* < *Take*
  - Agency =f(relative velocity)
- Mutliple-contact events
  - Give(agent, object, recipient)
  - Take(agent, object, recipient)

Give(2, 3, 1)

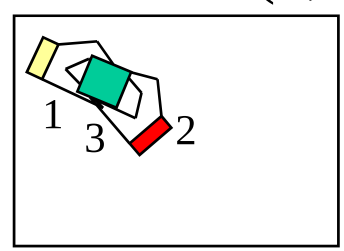


Contact (2, 3)



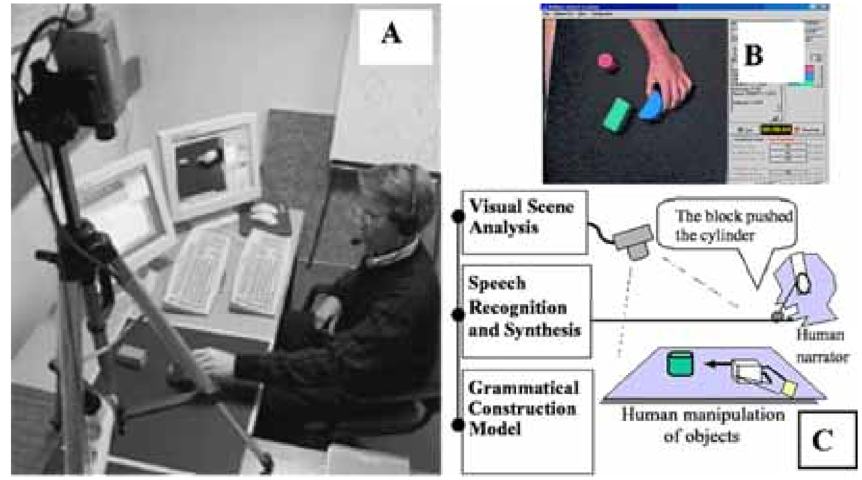
Contact (3, 1)

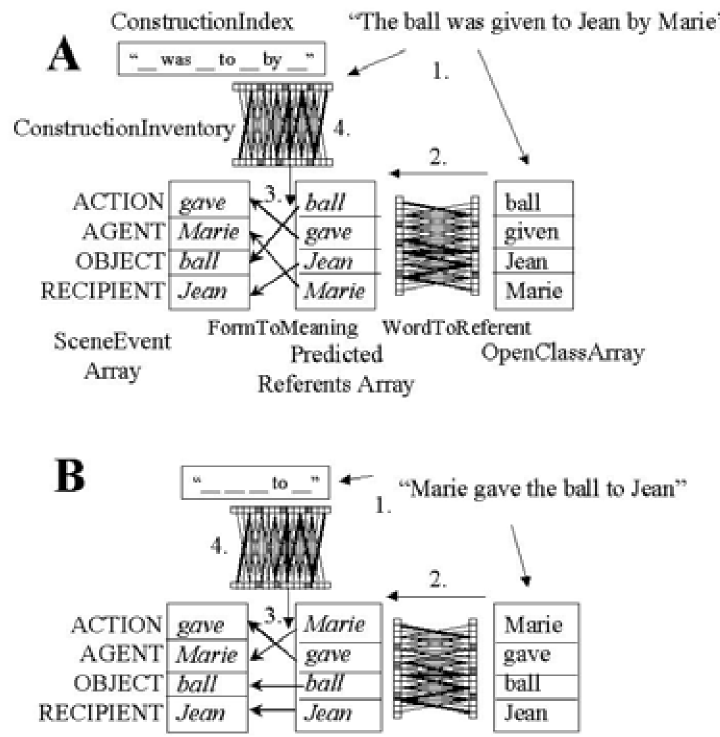
Contact (2, 1)



Grounded Sentence Learning

- Training corpus:
  - ~300 sentence-scene pairs
  - 10 Construction types
    - Active, dative, passive, relative ….
- “Developmental” Learning Trajectory
  - Simple SVO structure with full vocabulary
  - Then add datives, passives and relatives
- Why?
  - Learning new constructions requires that the constituent open class words are well-known so the appropriate mappings can be established





Dominey, Boucher (2005) Artificial Intelligence

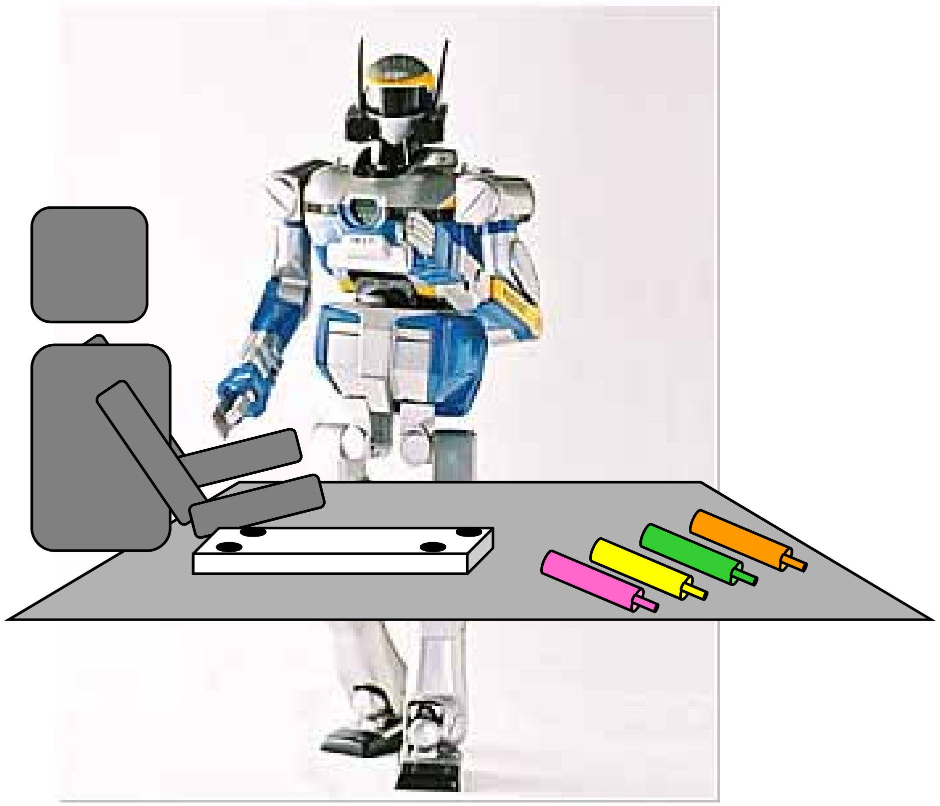
Learning grammatical constructions from naive human subjects in an “unconstrained” situation

- 4 Subjects Generate <Sentence, Meaning> pairs by narrating video events
  - 282 Sentence, meaning pairs:
- Train the model on ½ <Sentence, Meaning> pairs
- Test generalization on second ½
- 85% Accuracy on Training and Test sets

Dominey, Boucher (2005) Artificial Intelligence

Language-Based interaction with the Robot Apprentice

Cooperative Table Assembly Scenario



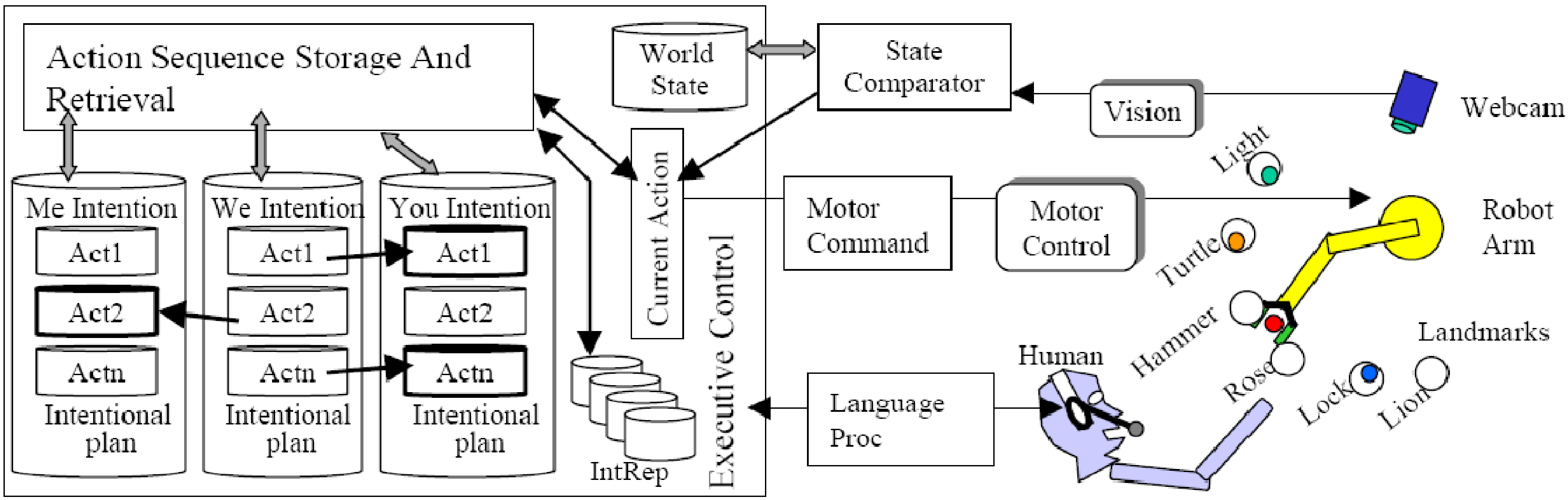
- Robot Helps Users to Assemble a Table
- Functional Requirements
  - The robot should be able to:
  - Respond to human spoken commands with simple behaviors
    - Open left hand, turn right,..
    - Grasp(X): X in <visible>
  - Learn complex behaviors constructed from the primitives
    - Give me the orange leg
    - Hold the table

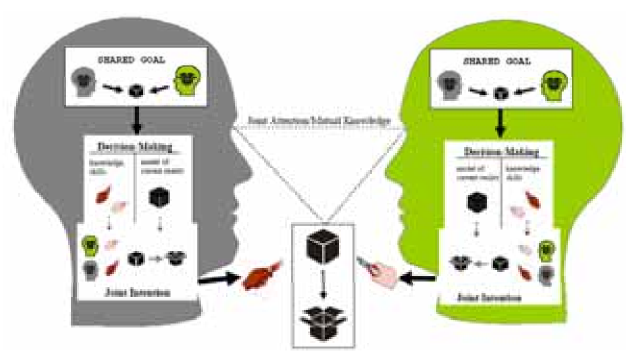
Using Verb Island Constructions To Teach New Behaviors

Dominey, Mallet, Yoshida (2007ab)
IEEE Intl. Conf. Robotics & Automation
IEEE Intl. Conf. Humanoid Robots

- Give me the X
  - X = (yellow, rose, green, orange) leg
  - Based on « Grasp (X) »
- Training with one example
  - X in «give me X » bound to X in « grasp X »
  - Learned procedure generalizes over X.
  - Powerful learning capability with procedures that take variables
- Embodiment of lexical categories
  - Verbs – procedures
  - Nouns - arguments

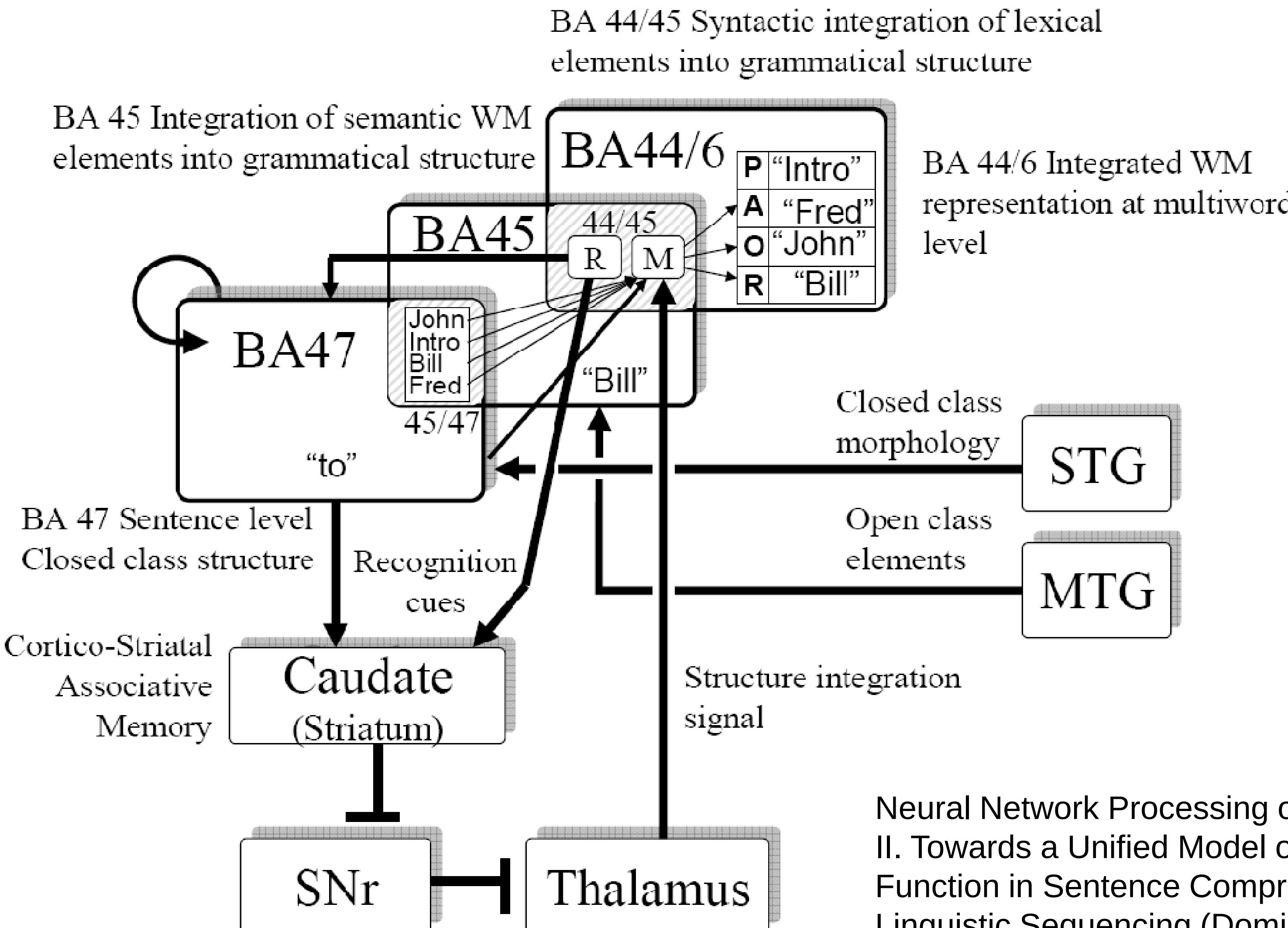
Ongoing research
(1) Language for Cooperation





The Basis of Shared Intentions in Human and Robot Cognition (Dominey & Warneken in Press.)

Ongoing research
(2) On-line sentence processing

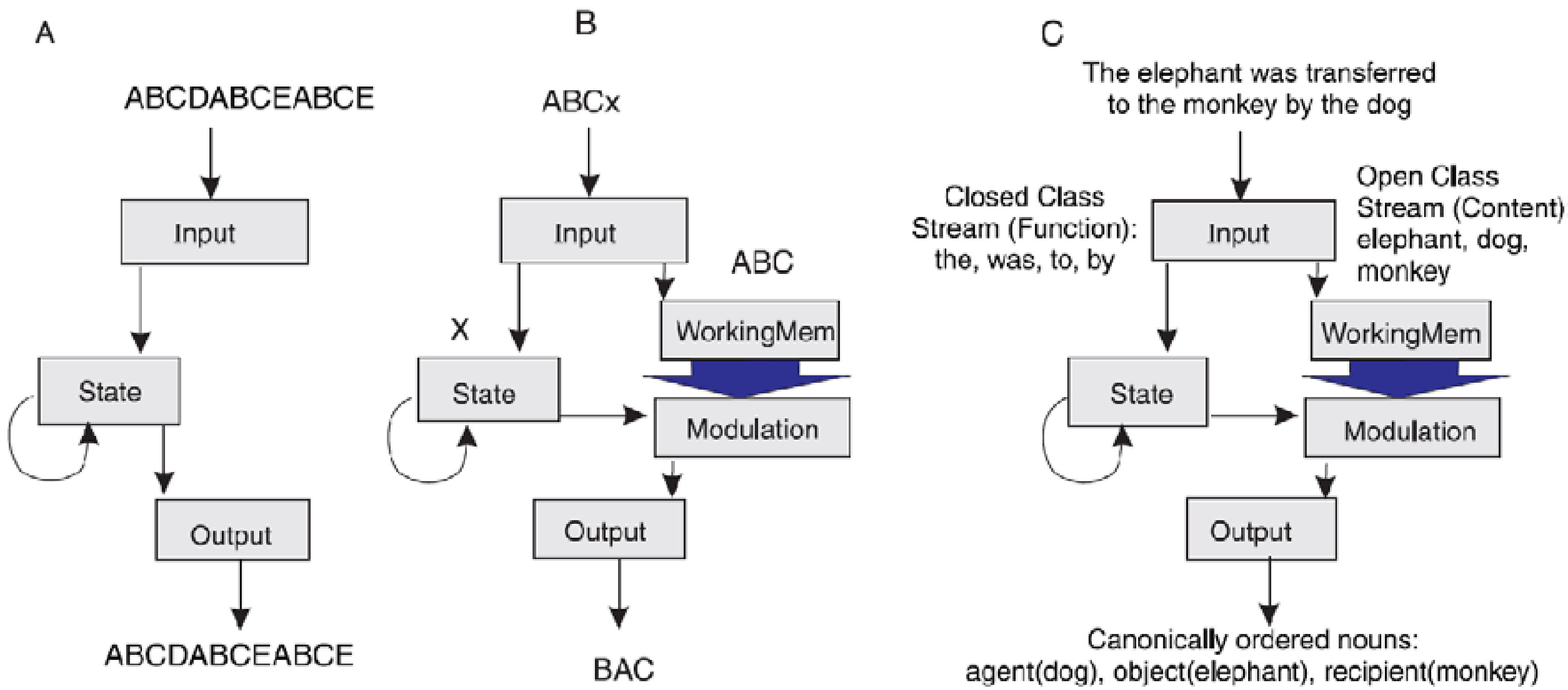


Neural Network Processing of Natural Language: II. Towards a Unified Model of Corticostriatal Function in Sentence Comprehension and Non-Linguistic Sequencing (Dominey & Inui Submitted)

Conclusion

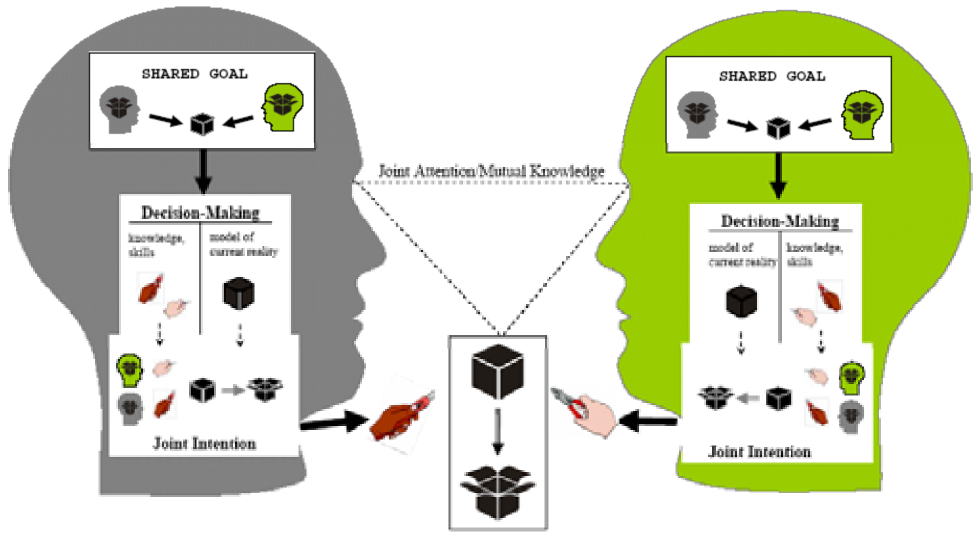
- Requirements on language: what is it for? – Cooperation
  - Linearlization of a high dimensional representation
- What strategies can be employed
  - Word order, grammatical markers, prosody, … Cue Competition
  - Grammatical constructions – form to meaning mapping
- How can this be realized in neurophysiology
  - Specialized working memories in BA47,45,44,6 and the corticostriatal system
- Testing
  - fMRI
  - Simulation
    - Cross lingustic learning
    - Insights into holophrase – abstract construction transition
  - Robotics
    - Learning from real data
    - Human Robot Cooperation
- Ongoing research
  - Shared intentions for robots
  - On-line neural network langauge processing

From Sensorimotor Sequence to Grammatical Construction: Evidence from Simulation and Neurophysiology



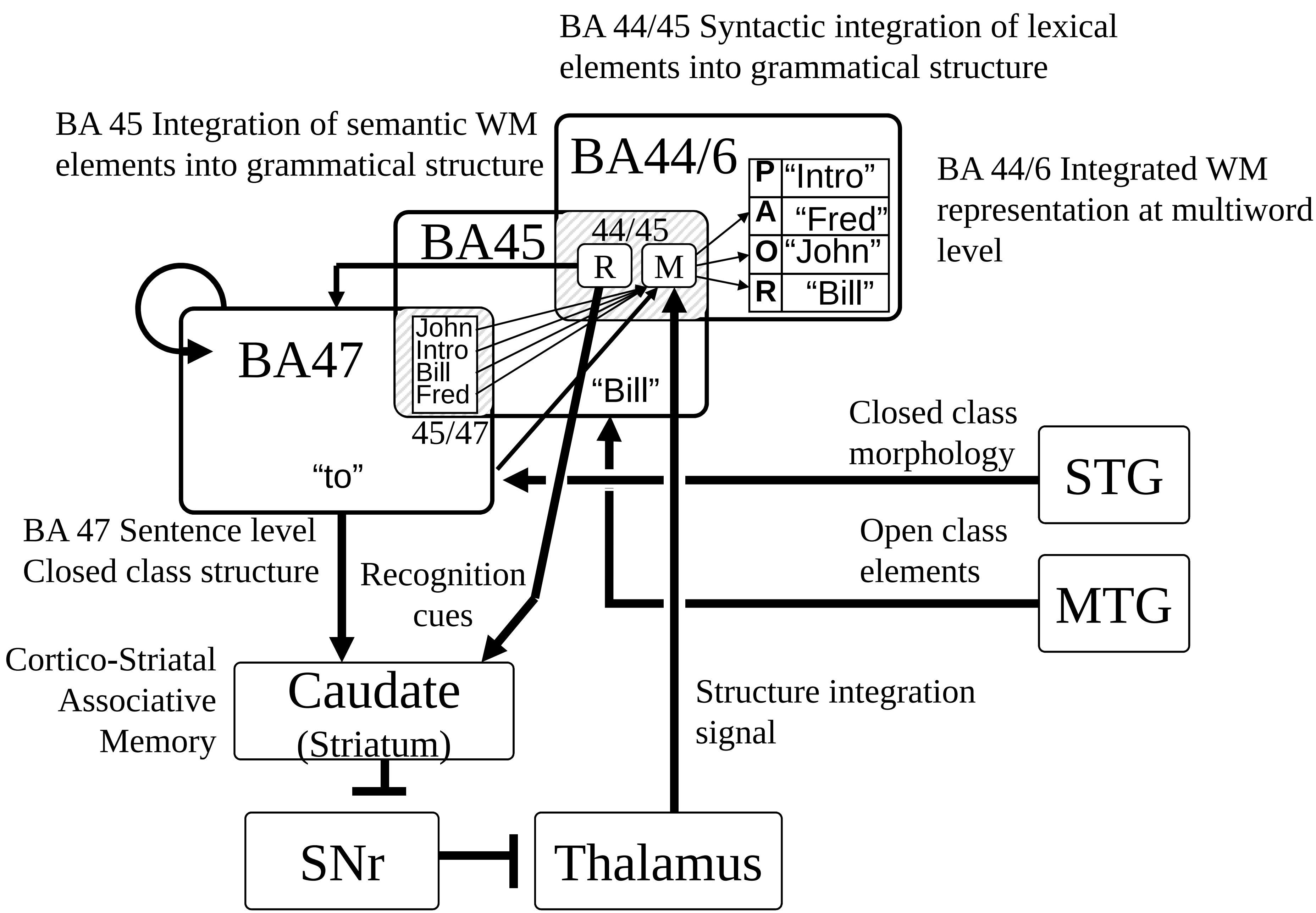
Something is wrong with this guy… He's a robot!

- So far the robot is used purely in an instrumental way
- It does't *know* what it is doing
- Can't simulate anything
- This requires additional representations
- Strategy: Investigate how this develops in children
- Warneken et al.
  - 18 month old child observes 1 or 2 examples of a game, and can then take over



Tomasello et al. BBS

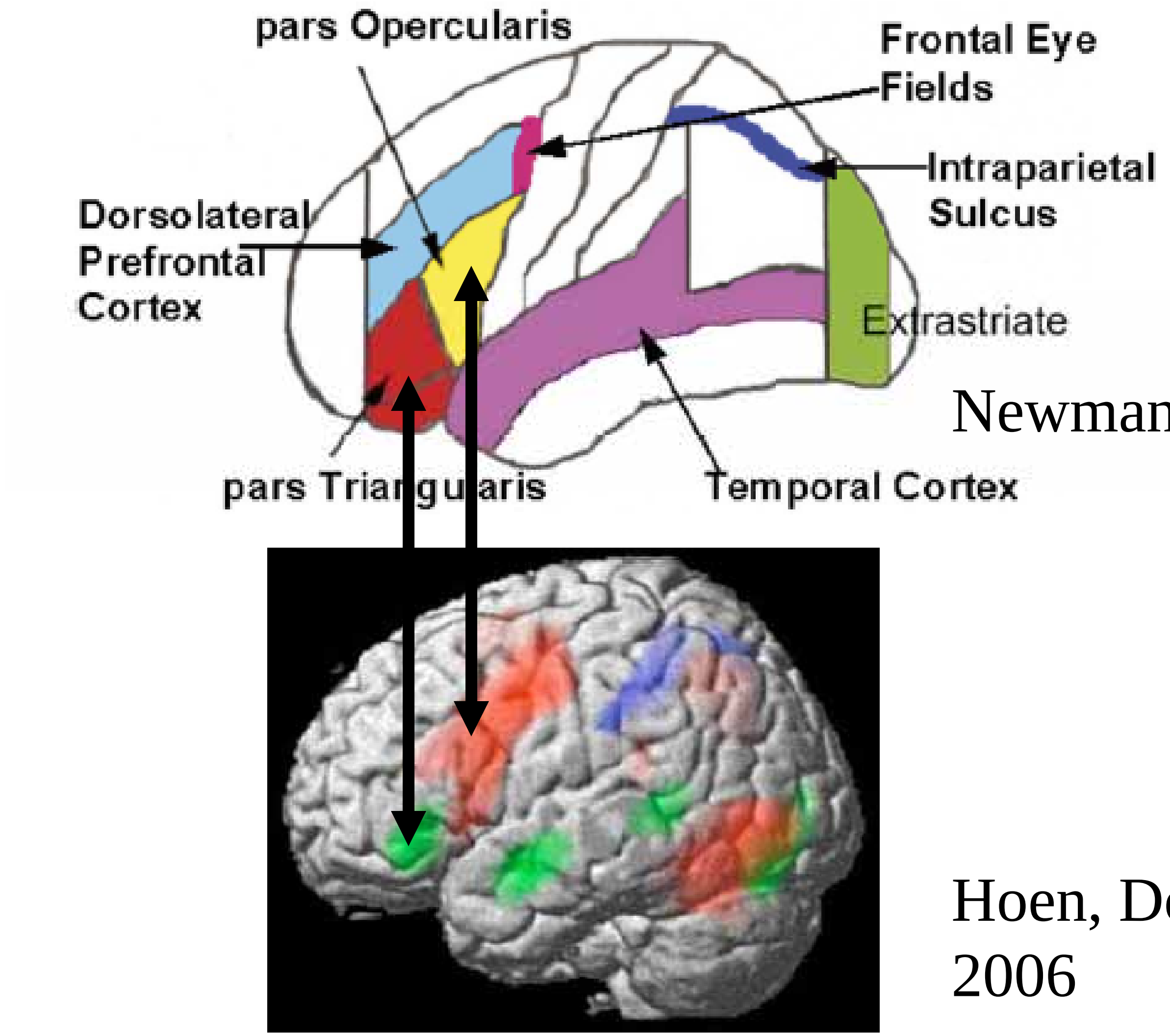
Warneken et al. 2006


BA 44/45 Syntactic integration of lexical elements into grammatical structure
BA 45 Integration of semantic WM elements into grammatical structure
BA44/6
P "Intro"
A "Fred"
O "John"
R "Bill"
BA 44/6 Integrated WM representation at multiword level
BA45
44/45
R
M
BA47
John
Intro
Bill
Fred
"Bill"
45/47
"to"
Closed class morphology
STG
Open class elements
MTG
BA 47 Sentence level Closed class structure
Recognition cues
Cortico-Striatal Associative Memory
Caudate (Striatum)
Structure integration signal
SNr
Thalamus

Conclusion

- The corticostriatal system for sequencing and working memory can be employed for language acquisition in the context of the competition model
  - Simulation
  - Neuroscience
  - Robotics

Neurophysiology: Shared cortical networks for abstract sequences and language



Newman et al. 2003

Hoen, Dominey et al. 2006

Example English and Japanese Constructions Learned

Dual-event Relative Constructions

6. The block that pushed the cylinder touched the moon.

   Push(block, cylinder), Touch(block, moon)

   6. Agent1 that verb1ed object2 verb2ed object3.

   Action1(agent1, object2), Action2 (agent1, object3)

18. The cylinder that was pushed by the block gave the cat to the dog.

   Push(block, cylinder), give(cylinder, cat, dog).

   18. Obj4 was act2ed from ag3 to recip1 that act1ed obj2

   Action1(agent1, object2), Action2 (agent3, object4, recipient1)

Dual-event Relative Constructions

The block that hit the circle pushed the triangle (6)

13. Circle-wo tataita block-ga triangle-wo oshita.

   Hit(block, circle), Pushed(block, triangle)

   13. Obj1-wo verb1 Agent1-ga Obj2-wo verb2.

   Verb1(Agent1, Obj1), verb2(Agent1, Obj2)

The block was hit by the triangle that pushed the circle (7)

14. Block-ga circle-wo oshita triangle-ni-yotte tatakareta.

   14. obj2-ga obj1-wo verb1 agent1-ni-yotte verb2

15. Circle-wo oshita triangle-ni-yotte block-ga tatakareta.

   Pushed(triangle, circle), Hit(triangle, block)

   15. obj1-wo verb1 agent1-ni-yotte obj2-ga verb2

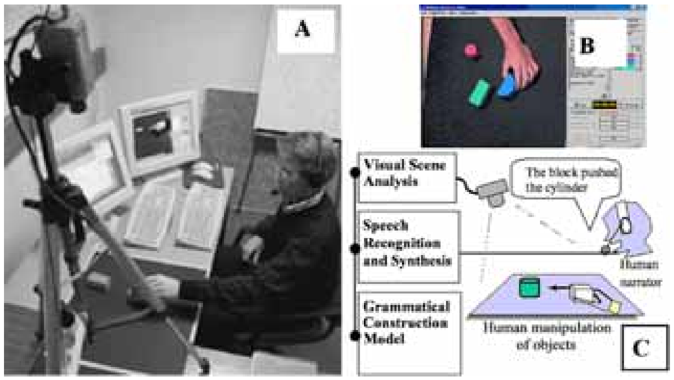
   Verb1(agent1, circle), Verb2(agent1, block)

(Dominey, Hoen, Inui 2006 J Cog Neuroscience)

Learning to talk about events from narrated video in a construction grammar framework

Peter Ford Dominey *, Jean-David Boucher

Artificial Intelligence 167 (2005) 31–61



Using Verb Island Constructions To Teach New Behaviors

Kawada Industries HRP-2 Platform
CNRS-AIST Joint Robotics Laboratory
LAAS, Toulouse, France

- The robot should be able to:
  - Respond to human spoken commands with simple behaviors
    - Open left hand, turn right,..
  - Learn complex behaviors constructed from the primitives
    - Give me the orange leg
    - Hold the table
- We must
  - Define a set of primitive actions that are pertinent to this task, and can generalize to other tasks
  - E.g. « open left hand »
  - E.g. « take X »
    - Vision of X
    - Localization for grasping

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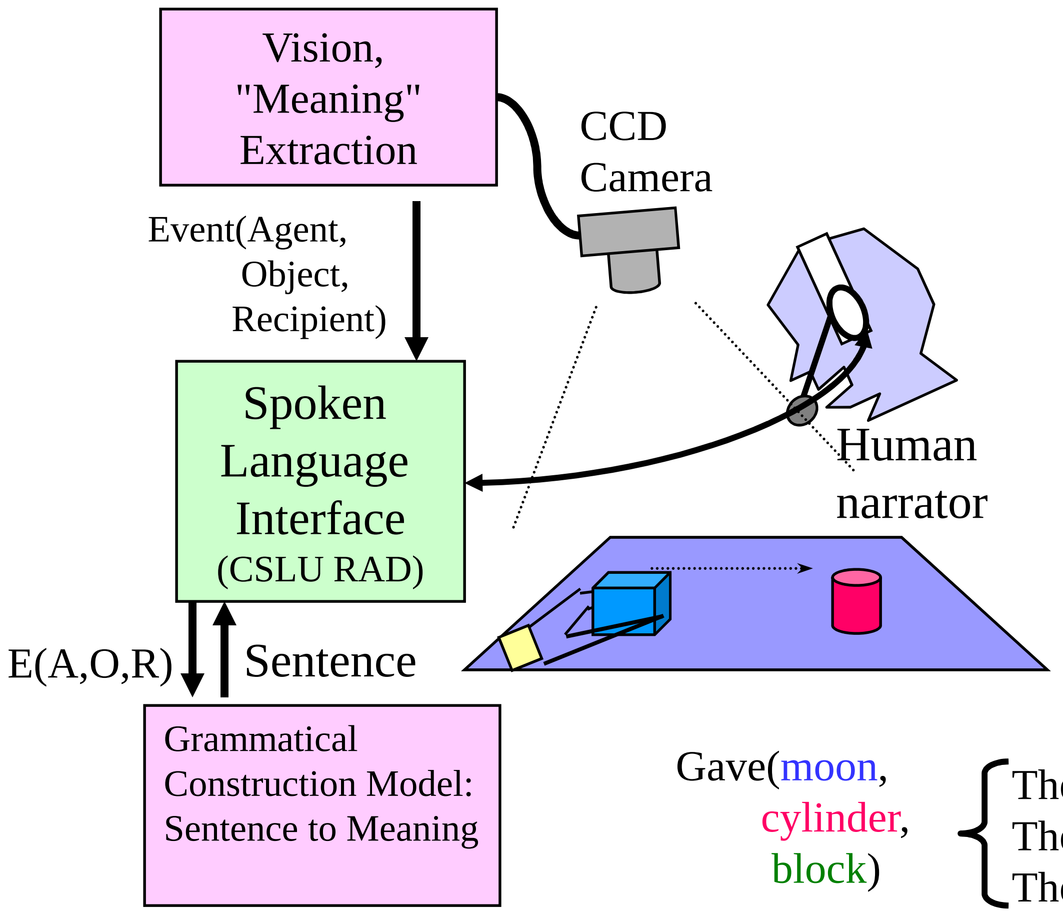
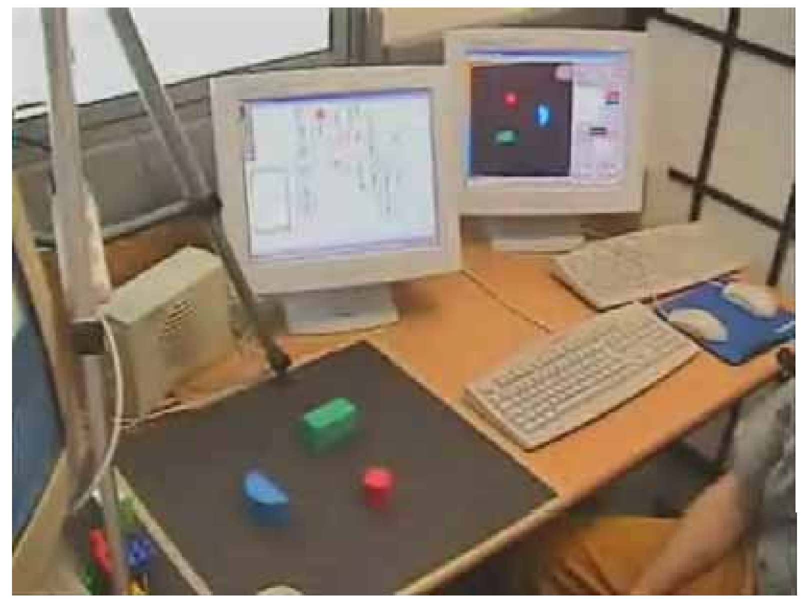
Using These Learned Grammatical Constructions for Event Description and Interrogation





The moon gave the cylinder to the block.
The block was gave the cylinder by the moon.
The cylinder was gave to the block by the moon.

Action Perception: Extracting meaning from vision