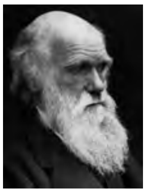
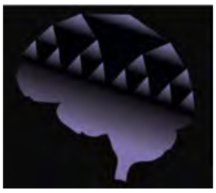
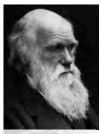
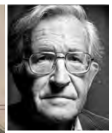
Towards a **computational** framework for **comparative** studies of sequence and **syntax**

W. Tecumseh Fitch
University of Vienna


Cognitive Biology: Building Bridges between Biology & the Cognitive Sciences



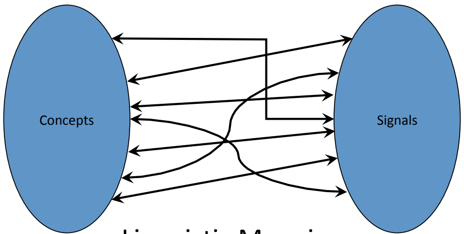


"Bio-Linguistics"

Big Questions in Language Evolution

- **Where** did language evolve? (Africa)
- **When** did language evolve? (sometime in the last six million years, finished by ~100K ago)
- **How** did language evolve? Saltation or Gradual? (Combination)
- **Why** did language evolve? Communication or Thought? (Both)
- **What**, exactly, evolved? What is language that it could evolve in our species and not others?

What is Language?

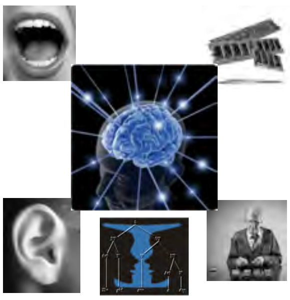


Linguistic Mapping

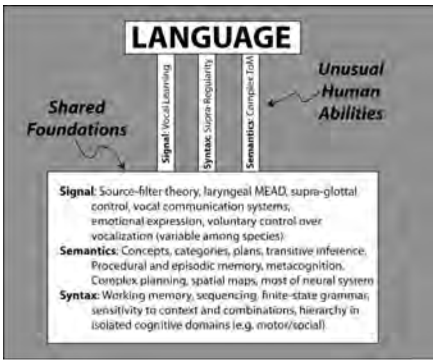
Language is a complex faculty that allows us to encode, elaborate and communicate our thoughts and experiences (via hierarchical phrases built up from arbitrary words).

"Divide-and-Conquer"

The Multi-Component Perspective of Modern Cognitive Science



Broadly Shared Biological Foundations



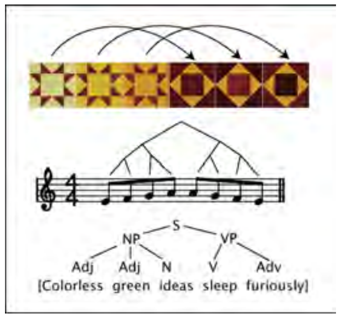
Comparison to Chimpanzees: *Three* **Novel Components of Language**

"Signal"
(Complex Signals: Vocal Control & Learning)

"Syntax"
(Compositional, Hierarchical, Processing)

"Semantics"
(Intent to Communicate, Pragmatics)

Syntax



Sign Language Trained Apes: Learn Only Very Simple Syntax


Washoe (chimpanzee)
Koko (gorilla)
Nim (chimpanzee)
Kanzi (bonobo


Savage-Rumbaugh et al (1993) Kanzi; Yang (2013) Nim Chimpsky

Language Makes "Infinite Use of Finite Means"

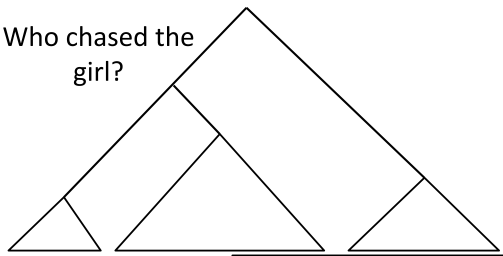
Wilhelm von Humboldt (1836):
p 106: "von endlichen Mitteln einen unendlichen Gebrauch machen"

Chomsky's Early Insights

- "Language" interpreted as a finite set of rules generating an unlimited set of sentences.
- Meta-mathematical tools of Turing, Church, and Post generate infinite sets with finite rules; these can be used to represent the linguistic rules: "grammar" in a new sense.

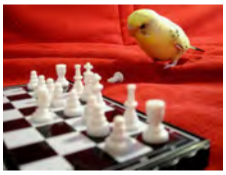
Hierarchy in Human Language a Key Feature: Structure Dependence

Who chased the girl?



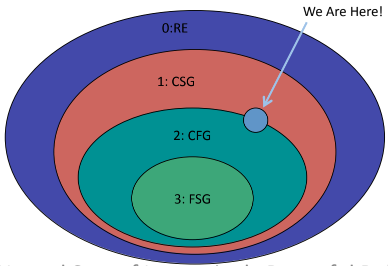
The boy who kicked the dog chased the girl.

Core Biological Issue: Hierarchical Pattern Perception

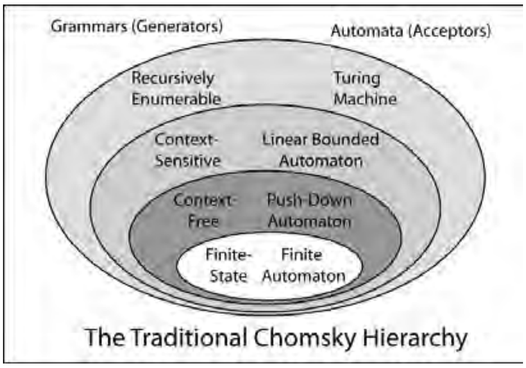


- Humans have a capacity, and propensity, to perceive rules of **hierarchy** and **symmetry**
- What are the biological basis and precursors of this "sense of order"?
- Earlier results (Huber & Aust 1999; Swaddle & Ruff 2004) show that starlings & pigeons cannot perceive abstract symmetry!

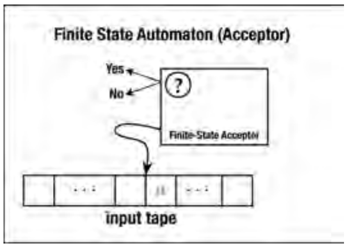
Road Map: The Formal Language Hierarchy



Nested Sets of Increasingly Powerful Rule Systems "Grammars" (Chomsky 1957)

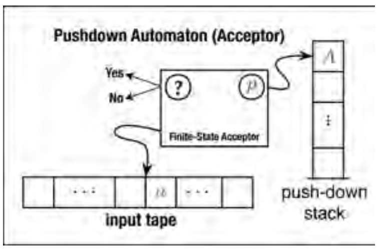


Finite State Automaton Example: Accepts $(ab)^n$



Kleene's Theorem: Strict equivalence between **regular languages** and deterministic **finite state automata**.

Context-Free Acceptor: Push-Down Automaton



Just a finite-state machine **augmented** with an additional memory system, termed a "**stack**"

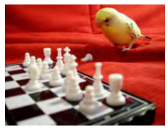
Trees: **Supra-Regular** Formal Grammars (e.g. Context-Free)

- Introduced by Chomsky and colleagues in late 1950's, as models of language between finite state machines and full Turing machine
- Also called "phrase structure grammars" or "constituent structure grammars"
- Just add a "stack" to a FSM

George Miller's Supra-Regular Hypothesis

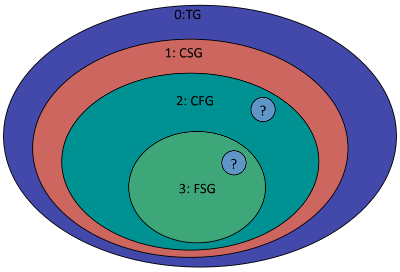
- George Miller (1967) "Grammarama" paper: "constituent structure languages are more natural, easier to cope with, than regular languages... easier for people than the left-to-right organization characteristic of strings generated by regular grammars"
- Humans attribute tree-structures to data, even where there is little evidence for it
- Bayesian Terms: Humans have a high "prior" on context-free, relative to finite-state, rules.

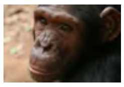
My Core Question Rephrased: **Supra-Regular Pattern Perception**?



- Humans are biased to perceive **tree structures** in arbitrary stimuli
- What about animals? Can they? Do they "find it more natural" (are they biased towards supra-regular rules)?

Comparative Research: Where do **animals** fit into the formal language framework?





Animal's Own Vocalizations?

Okanoya, ten Cate, Berwick and others: Birdsong can be well-modeled with finite state (regular) grammars: no need for supra-regularity.

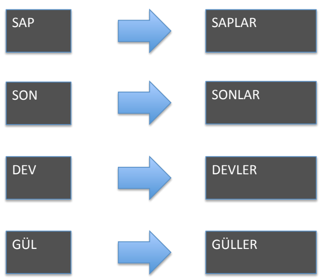
cf. ten Cate & Okanoya (**2012**) Phil Trans B **367**: 1984

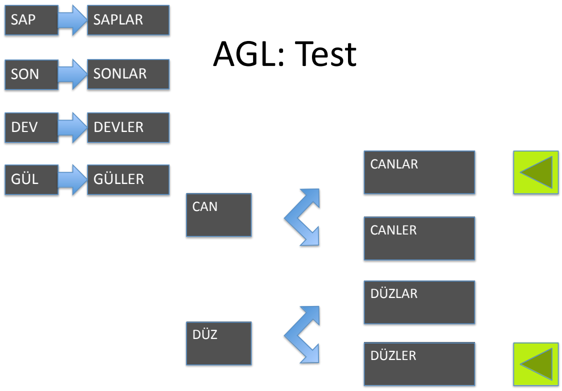
Possible exceptions: whales? mockingbirds? Still unclear.

Animal Pattern Perception: How to Examine it Empirically?

- **Key Idea**: Test subjects with pairs of grammars at two different formal levels
- Choose grammars matching on all other parameters (length, # element types, etc.)
- Multiple techniques available:
  - Artificial Grammar Learning – fast and easy
  - Operant testing and training – slow but MUCH more data for analysis

Artificial Grammar Learning: Training





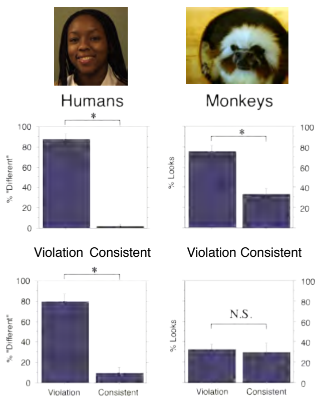
AGL: Test

Two grammars – Simple pattern generating algorithms

Sequential Rule (Finite State Grammar)

Hierarchical Rule (Context Free Grammar)

Cotton-top Tamarin Results



Sequential Rule (Finite State Grammar)

Hierarchical Rule (Context Free Grammar)

Fitch & Hauser (2004) Science

Fitch & Hauser Conclusion:

"These results suggest that, despite a clear ability to process sequential regularities in acoustic strings, **tamarins are unable to process a simple phrase structure**"

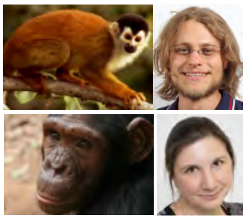
Further FLT in animals/neuroscience

- Fitch & Hauser (2004) – A^nB^n versus $(AB)^n$
- Perruchet & Rey (2005) – critique (humans)
- Gentner et al (2006) – A^nB^n in starlings
- Friederici et al (2006) – Brain regions
- De Vries et al (2008) – critique of *that*
- Van Heijningen (2009) – critique of Gentner…
- Abe & Watanabe (2011) – A^nB^n in Bengalese finches …
- Rey, Perruchet, Fagot (2012) - baboons

Replications and Critiques

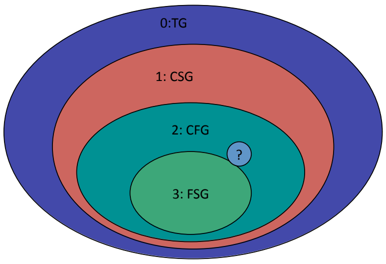
- Human results with *both* grammars now replicated repeatedly in multiple sensory modalities – a solid empirical finding.
- FSG in animals also now replicated repeatedly
- Still relatively few attempts at supra-regular grammars in animals

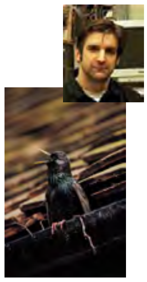
Another Regular Grammar of Interest: **AB*A**



Andrea Ravignani et al 2013: Biology Letters 9(6) – Squirrel monkeys
Ruth Sonnweber et al 2015: Animal Cognition 18(3) – Chimpanzees (visual)

Where are songbirds in the formal language hierarchy?

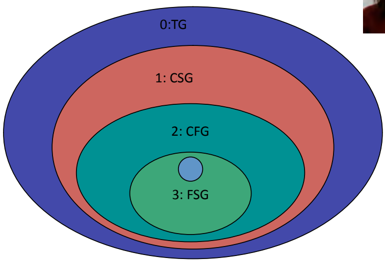




(Gentner et al 2006, Nature)

With intensive training, starlings appear to succeed on both $(AB)^n$, and supra-regular grammar A^nB^n. But…

Zebra Finch Results: The Dutch Challenge



(van Heijningen … ten Cate 2009, PNAS)

Some zebra finches can master the A^nB^n but they do so using a combination of simple finite-state rules!

Dutch Critique of Gentner's Conclusion

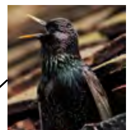
- Gentner et al excluded many possible regular alternatives, but omitted a key foil
- Crucially, they *pooled* individual results
- Further analysis shows that idiosyncratic finite-state strategies are used in zebra finches and nonetheless give the same results as for starlings when pooled

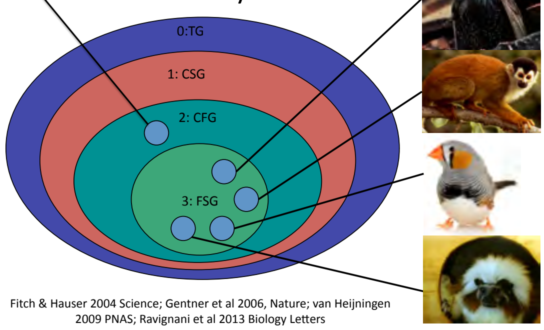
Van Heijnegen, Zuidema, ten Cate (2011) PNAS

Interim Conclusion: **Animal Auditory AGL**

- Humans are clearly competent with supra-regular grammars, spontaneously and without training.
- Animals are not. Even *with* intensive training their accomplishments are limited and currently disputed.
- But do acoustic strings provide a fair comparison?

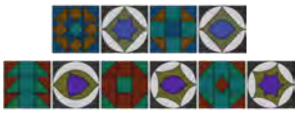
Graphical Summary: Artificial Grammar Learning: Auditory Stimuli



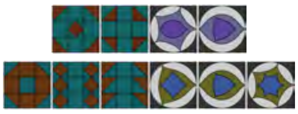


Fitch & Hauser 2004 Science; Gentner et al 2006, Nature; van Heijningen 2009 PNAS; Ravignani et al 2013 Biology Letters

Visual Artificial Grammar Learning



(AB)^n



A^nB^n

Nine Stobbe,
Ulrike Aust,
Gesche Westphal Fitch

The Central Empirical Issue:

- A string set may be *produced* by a CFG but still *recognized* by a regular grammar
- Need to exclude such regular alternatives
- For $\mathbf{A^nB^n}$ examine response to:
  - More transitions
  - “Starts with A”: “A.*”
  - “End with B”: “.*B”
  - “Some BA”: “.*BA.*”
  - Etc.

Three Critical Test Cases for A^nB^n

Can *every* subject tested…

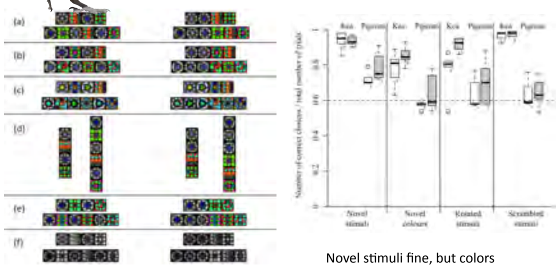
- Recognize novel stimuli that follow the pattern?
- Generalize over *n*: Train on n = 2, 3 then test with n = 4, 5. Termed “Extensions”
- Reject “Mismatched Foils”: **crucial**: probe strings where number of As and Bs do not match!

(neglected by many studies, e.g. Rey, Perruchet & Fagot (2012) test only with $\mathbf{A^2B^2}$)

Human Performance:
At or near ceiling for all tests, with *better* performance on A^nB^n

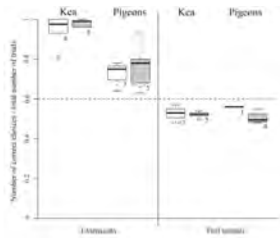
10 of 10 accept Extensions of n in A^nB^n
8 of 10 successfully reject unmatched A^nB^m

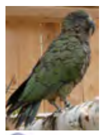
Keas: Successful with Multiple Generalizations



Novel stimuli fine, but colors problematic

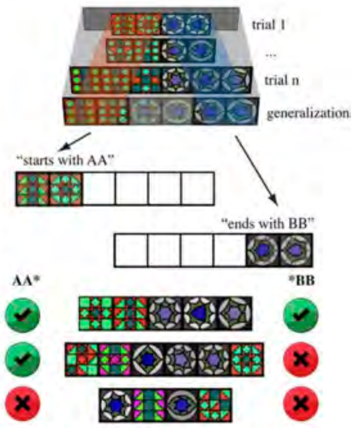
But on Crucial Unrewarded Probe Tests:
Keas generalize to longer strings, but Complete **Failure** on unmatched Foils!





Even given training, with feedback, on foils:
pigeons and keas cannot reject unmatched AnBn

Stobbe et al (2012) Philosophical Transaction of the Royal Society B



So what *are* they doing?

Model Selection Approach: Maximum Likelihood

Ravignani et al (2015) Cognition 143:13-24

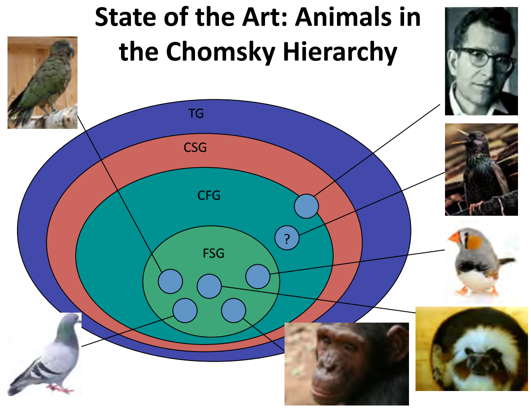
Finite-state Strategies Employed:

For $(AB)^n$: Ravignani et al (2015) Cognition 143:13-24

Conclusions

- Neither small-brained pigeons nor large-brained keas are able to recognize a simple supra-regular grammar, even after training.
- Consistent with previous finding of birds' failure to understand bilateral **symmetry**
- Also consistent with (current) failure of nonhuman primates to recognize supra-regular grammars

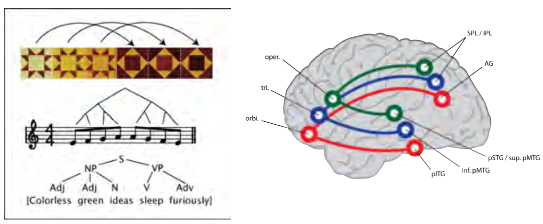
State of the Art: Animals in the Chomsky Hierarchy



The Dendrophilia Hypothesis

Current Working Hypothesis:

Humans have a species-typical, but **domain general**, ability and propensity to infer tree-formed, hierarchical structures from patterns. This entails computational resources above the finite state level and applies across music, language and the arts

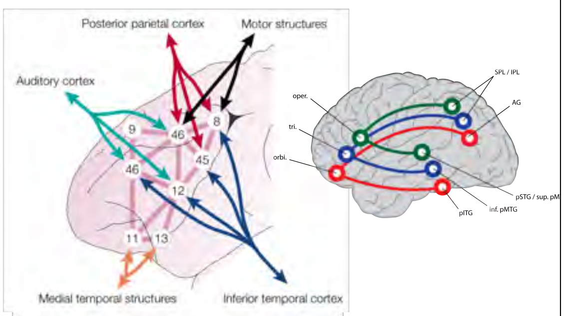


Conclusions

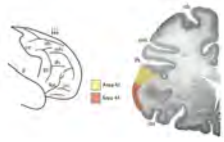
Neural Implementation?

Naturalizing Formal Language Theory.

Prefrontal cortex in general, and Broca's in particular, as the **hub** containing structure-building stack(s)

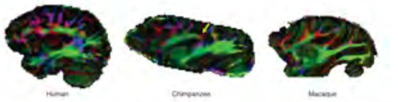


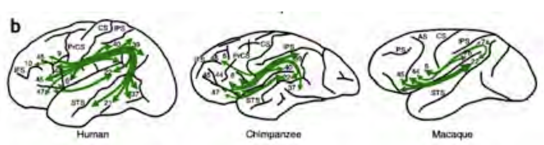
Natalie Schenker: Broca's Area (BA44/45) is the most expanded human cortical region known, relative to chimpanzees



Schenker et al (2010) Cerebral Cortex 20:730

Broca's: Significant Connectivity Changes

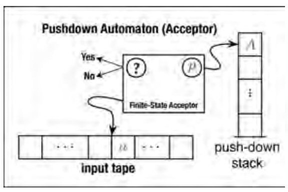


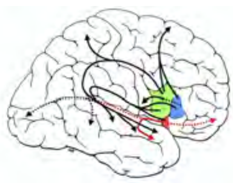


James Rilling et al 2008 Nature Neuroscience 11(4): 426-428

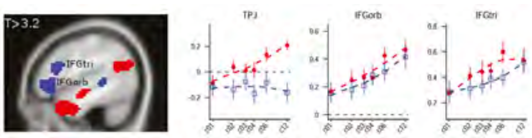
Hypothesis: Broca's & Supra-Regularity

Broca's provides a domain-general auxiliary memory (roughly equivalent to a "stack") to other brain regions





Broca's Area: Increasing Activity with increasing hierarchical chunk size



Jabberwocky" sentences with nonce nouns and verbs: BLUE is a significant chunk size effect, red show interactions

Pallier, Devauchelle, Dehaene (2011) PNAS 108: 2522

Theoretical Need for Bio-Linguistics:
<u>Formal Theory of Natural Computation</u>

- Formal Language Theory developed for mathematical purposes, not biology
- We eventually need a neurally grounded theory of "natural computation"
- Core issue: the specific computational and access structure of what psychologists call "working memory" (replacing the stacks, queues and tapes of FLT)

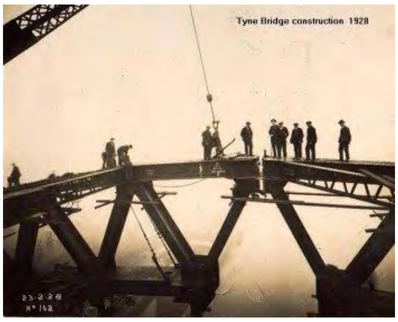
Conclusions

- Language can be fruitfully studied in a **comparative** manner (even though animals lack language)
- Human **syntactic** abilities are the hardest to find connections in animal communication
- The difference between human and animal syntax may be a human-specific **dendrophilia** – a proclivity to perceive hierarchical structure.

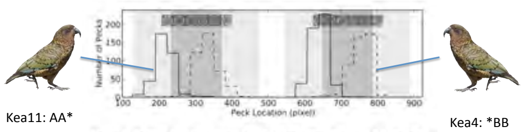
Thanks to…




Thank You!



Research Supported by **ERC Advanced Grant SOMACCA**, Austrian FWF Grant CogComm, and an EU FP6 Grant CHLaSC



Kea11: AA*

Kea4: *BB

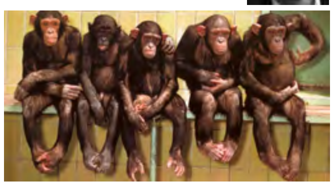
Figure 4: Pecking locations of two kea. K11 (unbroken line) and K4 (dashed).

Why Dendrophilic Cognition Matters

- Ability to infer "**hidden nodes**" of tree structures
- **Generativity**: A few example trees allow generation of many more via symmetry operations
- Can build both symmetrical and asymmetric (pruned) tree structures

Primates: Hierarchical Social Intelligence


Did hierarchical social relations provide cognitive precursor of hierarchical structure in humans?



The Cheney/Seyfarth Hypothesis, e.g. Seyfarth et al 2005 Trends Cognitive Sciences