Centre for Cognitive Science

Computational cognitive neuroscience:
9. Language

Lubica Beňušková
Centre for Cognitive Science, FMFI
Comenius University in Bratislava

Characteristics of language by O'Reilly

- ***Symbols.*** Language requires thought to be reduced to a sequence of symbols, transported across space and time (sound, text), to be reconstructed in the receiver's brain.
- ***Syntax.*** Language obeys complex abstract regularities in the ordering of words and letters/phonemes.
- ***Temporal extent and complexity.*** Language can unfold over a very long timeframe (e.g., Tolstoy's War and Peace), with a level of complexity and richness that far exceeds any naturally occurring experiences that might arise outside of the linguistic environment.
- ***Generativity.*** Language is "infinite" in the sense that the number of different possible sentences that could be constructed is so large as to be effectively infinite. Language is routinely used to express new ideas.
- ***Culture.*** Language shapes our cognition by means of cultural transmission relayed through language.

Is human language inborn or learned ?

B.F. SKINNER (1904 –1990)

Language acquisition is a

learning process based on the behaviouristic principle of conditioning (stimulus – response).

(Verbal Behaviour, 1957)

Noam CHOMSKY (1928 –)

Language is innate and unfolds because human beings are born with universal principles of grammaticality.

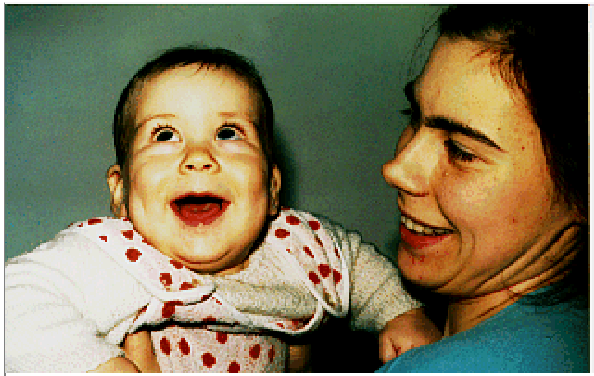
(Syntactic Structures, 1957)

The truth lies in between, i.e. there is a genetic basis for human language, but this language module has to be trained with proper stimuli during the critical period of development.

The "language gene" FOXP2

[Svante Pääbo et al, Nature, August 2002
Max Planck Institute of Evolutionary Anthropology]

- Two functional copies of FOXP2 (from mom and dad) are required for the development of the normal language in humans.
- Mutations of FOXP2 causes decreased activation in the putamen and Broca's area in fMRI studies.
- Patients have delayed onset of speech, difficulty with articulation including, slurred speech, stuttering, and poor pronunciation, as well as dyspraxia.
- Major part of this speech deficit comes from an inability to coordinate the movements necessary to produce normal speech including mouth and tongue shaping.
- FOXP2 has been conserved for about 200,000 years.
- Modern humans share the same allele as Neanderthals.
- The FOXP2 gene is more active in girls than in boys' genome.



Stages of development in the acquisition of language in humans

Average age	Language ability
6 months	Beginning of distinct babbling.
1 year	Beginning of language understanding, one-word utterances.
1 $^{1}/_{2}$ years	Words used singly, child uses 30-50 words (simple nouns, adjectives, action words) one at a time but cannot link them to make phrases, does not use functors (the, and, can, be) necessary for syntax.
2 years	Two-word (telegraphic) speaker, 50 to several hundred words in the vocabulary, much use of two-word phrases that are ordered according to syntactic rules, child understands propositional rules.
2 $^{1}/_{2}$ years	Three or more words in many combinations, functors begin to appear, many grammatical errors and idiosyncratic expressions, good understanding of language.
3 years	Full sentences, few errors, vocabulary of around 1000 words.
4 years	Close to adult speech competence.

Sue Savage-Rumbaugh, Kanzi & Panbanisha

- Young bonobos can learn to associate words with pictographic symbols during conversations centred around food, playing, and other daily routines.
- They can learn hundreds of concrete and some abstract meanings (like bad, good, a monster, nice, etc.) and use them creatively.
- After 10 years of training, comprehension as a 2 & 1/2 year old child, i.e. the word that precedes the object is to be treated as a verb, treat an object as an agent when it precedes the verb, etc.
- Production as a 2 year old child: two-word sentences.
- Documentary: https://www.youtube.com/watch?v=dBUHWoFnuB4

Critical period in learning the language

- The **Critical Period Hypothesis** states the first few years of life constitute the time during which language develops readily and after which the language acquisition is less successful or even impossible (Penfield & Roberts 1959).

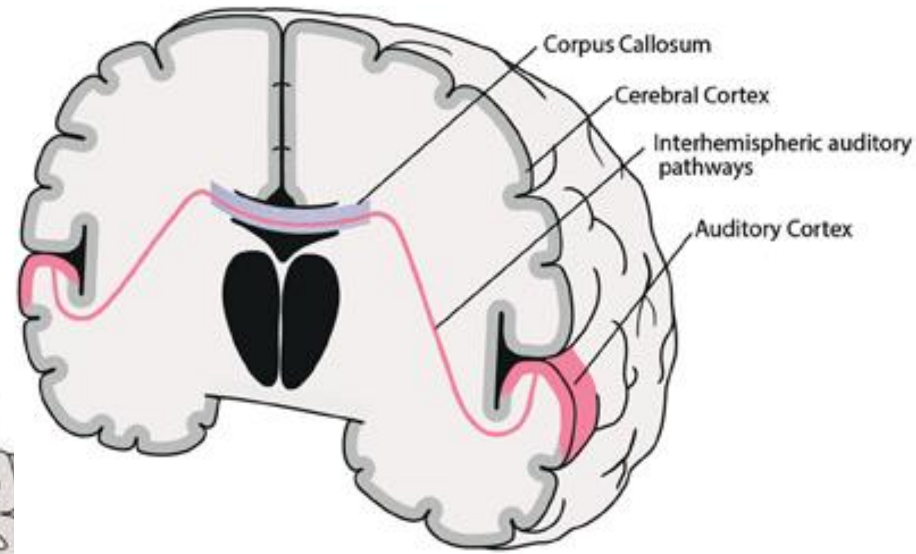
- Well documented cases of children who failed to acquire language after the critical period are Genie and Victor of Aveyron (both saved at age 13y) https://www.youtube.com/watch?v=cS8pptjr1E0

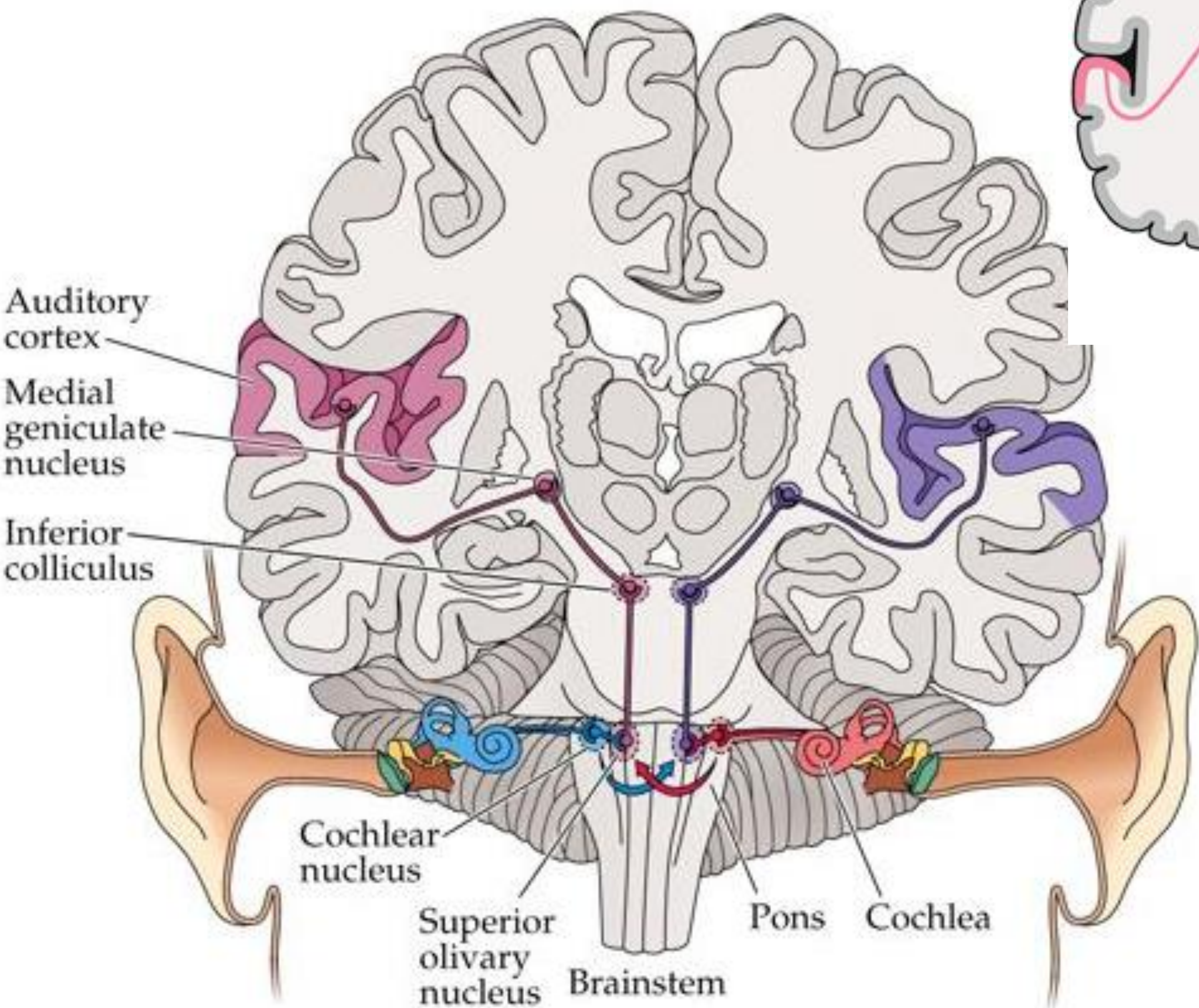
- Oksana Malaya (saved at 8y) has developed language (https://www.youtube.com/watch?v=nv3ocntSSUU).

Cognitive neurobiology of language (O'Reilly)

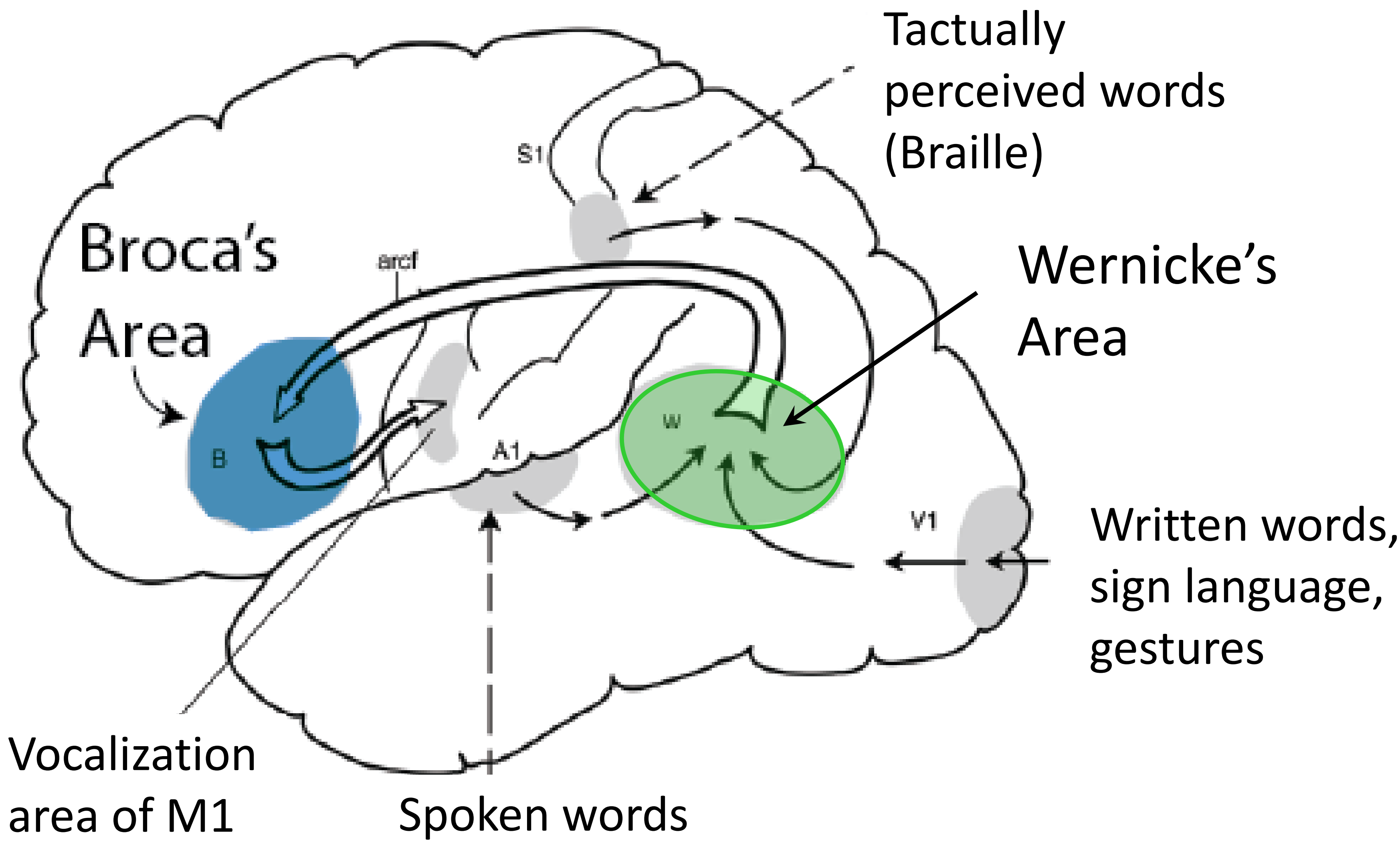
- ***Perception and attention:*** language requires perception of words from auditory sound waves or a written text or signs. Attention is critical for pulling out individual words and distinguishing individual speakers.
- ***Motor control:*** Language production requires motor output in the form of speech, writing, etc. In addition to the neocortex, fluent speech depends on an intact cerebellum, and the basal ganglia have been implicated in a number of linguistic phenomena.
- ***Learning and memory:*** early word learning depends on episodic memory in the hippocampus, while long-term memory for word meaning depends on learning in the cortex. Memory for recent topics of discourse and reading likely involves the hippocampus and sophisticated semantic representations in the cortex.
- ***Executive functions:*** language depends critically on the working memory from the prefrontal cortex (PFC) and basal ganglia – for example encoding syntactic structures over time, pronoun binding, etc.

The central auditory system





Main language areas in the cortex



- Broca's area (B) and Wernicke's area (W) are the main language areas located in the perisylvian language area, joined by the arcuate fasciculus (arcf).

Aphasia = language impairment

- **Broca's** and **Wernicke's** areas have been associated with **syntax** and **semantics**, respectively.

- A person who suffers a stroke or other form of damage to **Wernicke's area** can produce fluent, syntactically-correct speech, which is essentially devoid of meaning. It's called ***receptive aphasia***. Here is one example:
  - "You know that smoodle pinkered and that I want to get him round and take care of him like you want before", which, based on the situation, was intended to mean: "The dog needs to go out so I will take him for a walk".

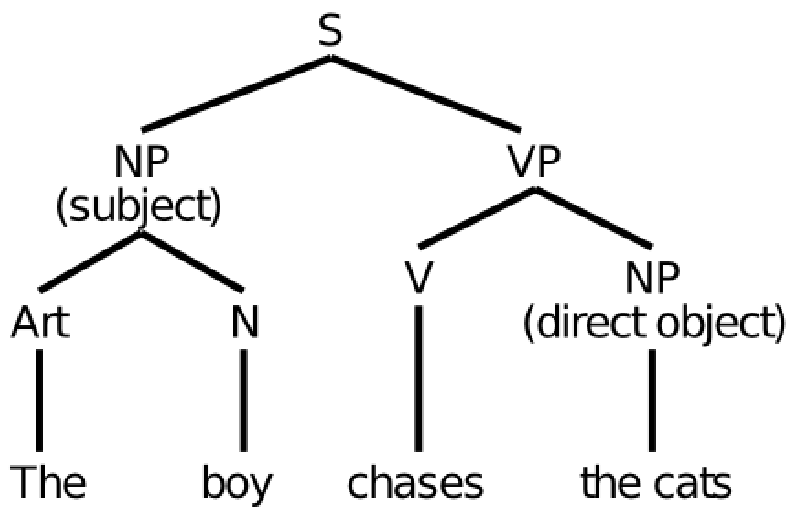
- In contrast, a person with damage to **Broca's area** has difficulty producing syntactically correct speech output, typically producing single content words with some effort, e.g., "dog....walk". It's called ***expressive aphasia***. Comprehension is typically intact, although there can be deficits in understanding more syntactically complex sentences

Broca's and Wernicke's areas

- The ventral posterior area of frontal cortex known as Broca's area (i.e., Brodmann's areas 44 and 45) is adjacent to the primary motor area associated with control over the mouth, and thus it represents supplementary motor cortex for vocal output.
- Even though Broca's patients can physically move their mouths and other articulatory systems, they cannot perform the complex sequencing of these motor commands that is necessary to produce fluid speech.
- Interestingly, these higher-order motor control areas also seem to be important for syntactic processing, even for comprehension. This is consistent with the idea that frontal cortex is important for temporally-extended patterning of behaviour according to increasingly complex plans as one moves more anterior in frontal cortex.
- The location of **Wernicke's area** in temporal cortex is sensible, given that we know that the temporal lobe represents the **semantic meanings** of objects and other things.

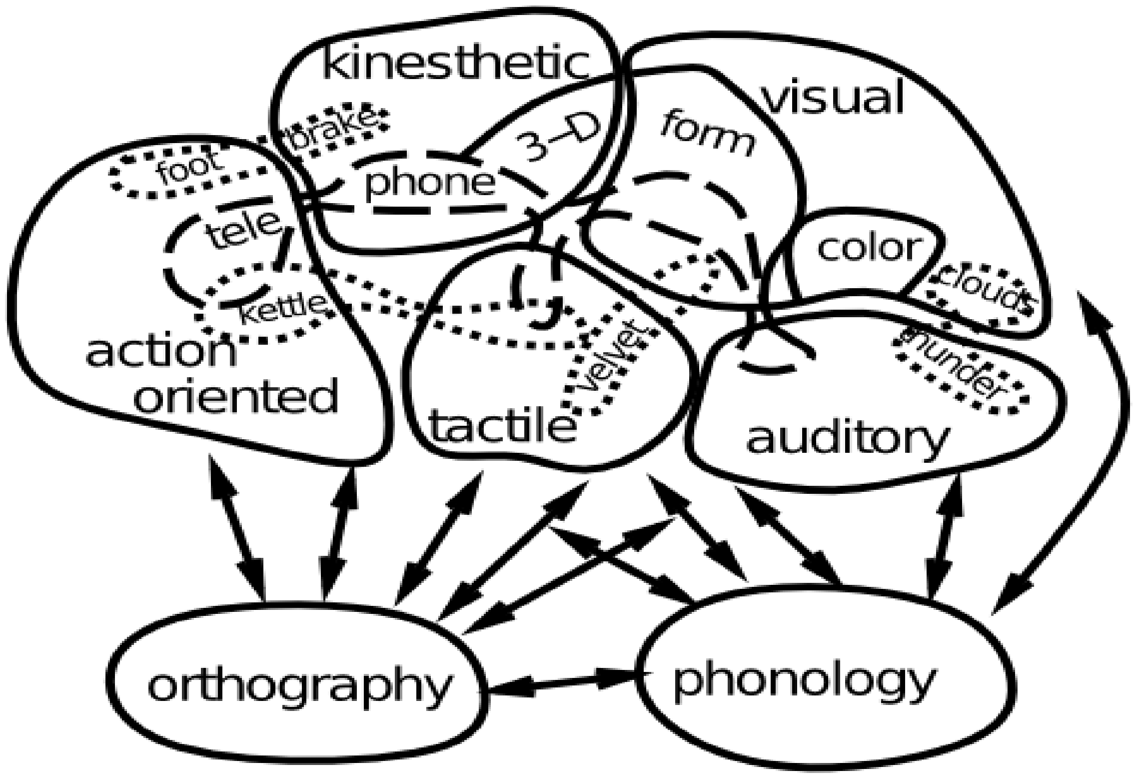
Syntax

- **Syntax** is a particular way of combining and ordering elements such as verbs and noun phrases to form a sentence in a given language.
- English is an **SVO language**, that is, in simple declarative sentences the order of the main components is **subject–verb–object**(s)
- The figure shows a syntactic diagram of a basic SVO sentence:



- S = sentence; Art = article; N = noun; NP = noun phrase; V = verb; VP = verb phrase.
- The SVO syntax is the most common, but there are languages with all kinds of syntactic rules, i.e. SOV, OVS, VSO, etc.

Semantics



- The **meaning of words** is encoded by **patterns of activity** within domain-specific brain areas that process sensory and motor information.
- These patterns of activity are re-created based on synaptic weights learned during memory consolidation.
- **Semantics is distributed throughout the brain**, and it is grounded in the sensory-motor primitives that we first acquire in life (tactile, action oriented).

Semantics of abstract words from word co-occurrence

- One compelling idea here is that words obtain their meaning "from the company they keep" – i.e., **the statistics of word co-occurrence** across the large volume of verbal input that we are exposed to.

- Thus, words that appear in similar contexts are **semantically related** to one another and consequently will be close in distance to one another in an abstract N-dimensional matrix space.

- One successful approach to capturing this idea in a functioning model is called Latent Semantic Analysis (LSA). It uses a neural network-based word embedding model trained on a large corpus of text to predict either a word given its context or the context surrounding a given word [http://wordvec.colorado.edu/].

Syntax and semantics in a sentence gestalt

- O'Reilly fosters an alternative way of thinking about sentence processing, which is based on a gestalt principle and is called the **Sentence Gestalt** model.

- The key idea is that both syntax and semantics merge into a developing distributed representation that captures the overall gestalt meaning of a sentence, without requiring all the precise syntactic bindings assumed in the traditional (i.e., symbolic) approach.

- The gestalt principle can deal also with **metaphors** ("to put the baby to sleep" versus "to put the cat to sleep") and **idioms** ("to kick a bucket").

- Similar gestalt-like theory of semantics, i.e., the theory of conceptual spaces was introduced by Peter Gärdenfors, MIT Press, 2001.

Gestalt principles in the word processing

- "Aoccdrnig to a rscheearch at Cmabrigde Uinervtisy, it deosn't mttaer in waht oredr the ltteers in a wrod are, the olny iprmoetnt tihng is taht the frist and lsat ltteer be at the rghit pclae. The rset can be a toatl mses and you can sitll raed it wouthit porbelm. Tihs is bcuseae the huamn mnid deos not raed ervey lteter by istlef, but the wrod as a wlohe."

- Explanation: People read words as whole units (gestalts), not letter-by-letter.
  - The words need to be relatively short.
  - Letters beside each other in a word can be switched without much difficulty for the reader to understand. When letters farther apart are switched, it's harder. Take porbelm vs. pelborm (for "problem").
  - We understand scrambled words better when their sounds are preserved: toatl vs. talot (for "total").
  - **The passage is readable because it's predictable** (especially because we've seen it so many times)!

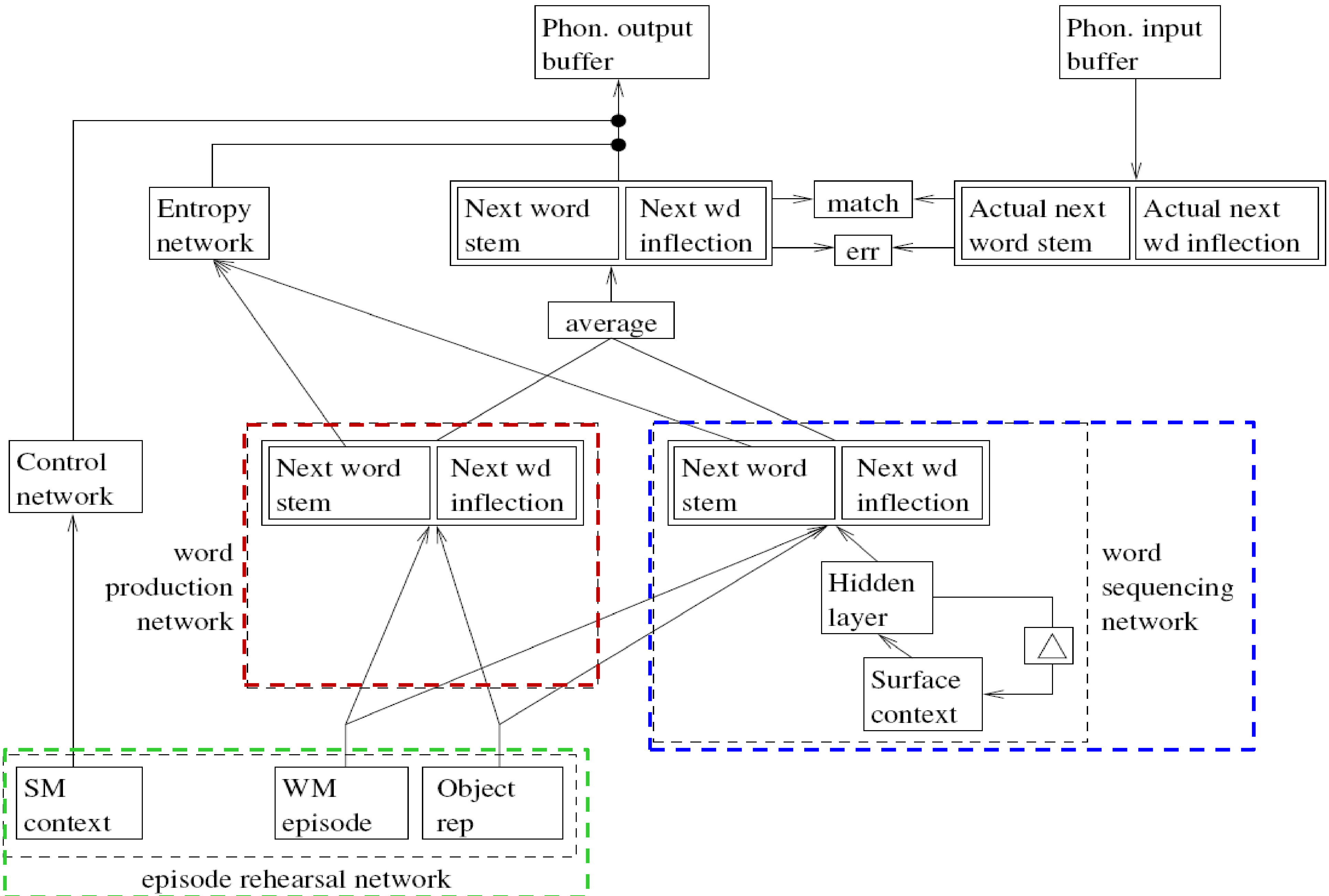
Link between language and sensorimotor cognition

- Alistair Knott has proposed a linking hypothesis between influential theories of language syntax (Chomsky, 1995) and sensorimotor cognition (Ballard et al., 1997).
  - Knott A: Sensorimotor Cognition and Natural Language Syntax. The MIT Press, Cambridge, MA, 2012.

- The core of hypothesis: the **syntax** of a sentence reporting a concrete episode in the world directly **relays the sensorimotor routine** through which the episode was perceived (https://www.youtube.com/watch?v=qhqLoTKBRz0)

- This is expressed as a **neural network model** of infant language acquisition that is trained using sentences from a real language (English, Maori, Slovak) in collaboration with Martin Takáč and myself (Cognition, 2012, 125: 288-308).

Schematic of neural network for language acquisition



Conclusion

- The main new idea is that episode representations are structured as sequences of semantic elements. Episodes' structure reflects the sequential structure of the sensorimotor (SM) routines through which they are experienced.

- The model is exposed to a corpus of sentences and can learn any word order grammar (SVO, SOV, etc.).
  - The grammar's 105-word vocabulary consisted of English words commonly used by 16–30 month toddlers. There were cca 4000 sentences.

- Emergent property was that the model went through "developmental stages" from production of one-word utterances through proto-syntactic constructions to full syntax and correct word morphology.