Language and the Brain

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Ma191b: Geometry of Neuroscience

- Jonathan R. Brennan, *Language and the Brain*, Oxford, 2022

What is language?

- What is Language? (langage, lenguaje, ...)
- What is a Language? (lange, lengua,...)

Similar to 'What is Life?' or 'What is an organism?' in biology

• *natural* language
as opposed to artificial (formal, programming, ...) languages

• The point of view we will focus on:
Language is a kind of *Structure*

- It can be approached mathematically and computationally, like many other kinds of structures
- The main purpose of mathematics is the understanding of structures

- there are many difference *languages* (more than 7000 are classified); more than 200 language-families, plus isolated languages (not fitting known families)
- languages change over time (historical linguistics)
- variability is *not* arbitrary: language is an extremely structured system
- spoken language (auditory cortex) ... *but* not always: signed languages; reading/writing
- computational structure
- very recent evolutionary development (structural differences with forms of animal communication like primates, songbirds, cetaceans)

Levels of Structure

A language exists at many different levels of structure

- Phonology: *sound* structures, building blocks (phonemes), tone systems, phonetics (physical aspects)
- Morphology: *words* (roots, affixes, stress), building blocks (morphemes), morphological typology (use of morphemes), lexicology, word formation, paradigms (words associated to same lexeme, conjugation, declension), morphosyntax

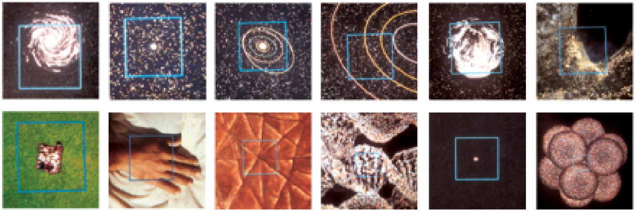
- Syntax: ($\sigma\upsilon\nu\tau\alpha\xi\iota\varsigma =$ ordering together) *sentences* core computational process of sentence building (I-language), hierarchical structures, movement/transformations, cross-linguistic syntactic variation (syntactic parameters), interface with sensory-motor system (externalization), interface with conceptual-intentional system (syntax-semantics interface)
- Semantics: *meaning*, semantic parsing of syntactic structures, semantic spaces (proximity, similarity), truth values (formal logic, propositional calculus)

syntax is the large-scale-structure of language and the key computational mechanism, also what clearly distinguishes human language from animal communication, key focus in understanding what language *is* as a structure

An analogy

Physics looks very different at different *scales*:

- General Relativity and Cosmology ($\geq 10^{10}$ m)
- Classical Physics (~ 1 m)
- Quantum Physics ($\leq 10^{-10}$ m)
- Quantum Gravity (10^{-35} m)



Despite dreams of a Unified Theory, we deal with different mathematical models for different levels of structure

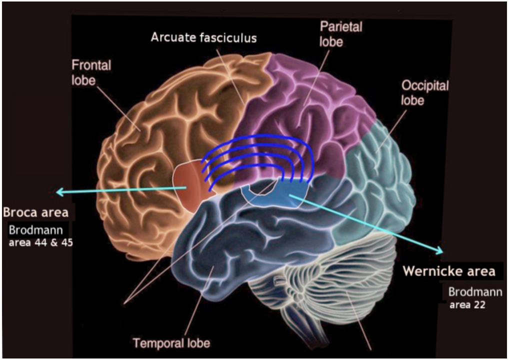
Similarly, we view language at different “scales”:

- units of sound
- words
- sentences
- global meaning

We expect to be dealing with different mathematical structures and different models at these various different levels

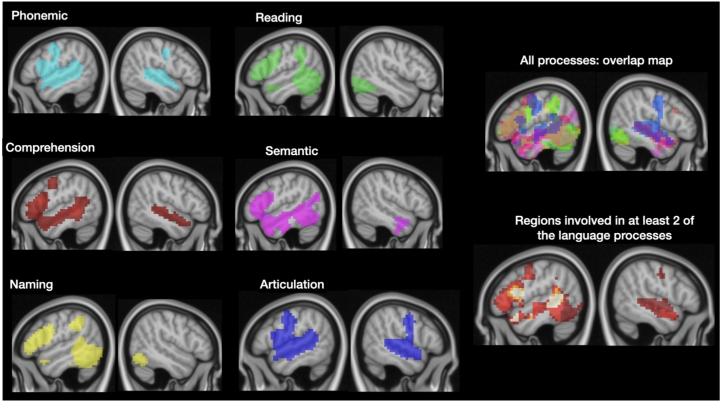
Mechanisms in the brain involved in language also vary according to these different scales

Language in the brain: early observations

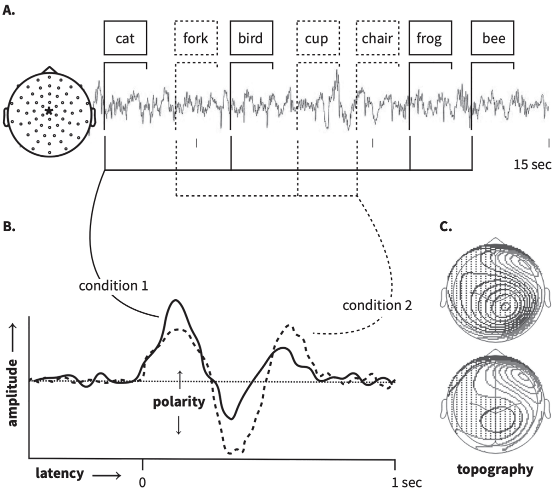


- observations on patients with compromised language capacities following various types of brain damage
- Pierre Paul Broca, 1860s: localization, left frontal lobe, Broca's area involved in speech production
- Carl Wernicke, 1870s: language relies links between frontal and temporal lobes (speech production and speech comprehension) Wernicke's area

Methods for studying language in the brain



- fMRI functional imaging, senses differences in blood oxygenation BOLD signal (blood oxygenation-level dependent), identifies well location of brain activity, but *slow* (low temporal resolution: seconds against millisecond speed of neural activity, also speech is 2-6 words/sec)

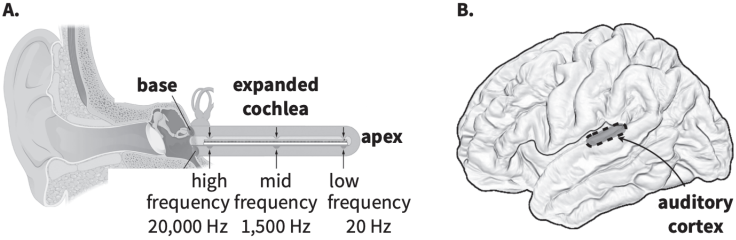


- electrical activity: electrophysiological techniques (high temporal resolution, not very good spatial resolution: source of signal): EEG (electroencephalography) and MEG (magnetoencephalography, higher spatial resolution than EEG)

- TMS (transcranial magnetic stimulation): strong and focused magnetic field to induce or inhibit electrical currents in the cortex, few millimeters resolution for target area, induce an action potential or inhibit neural activity (virtual lesions)
- DCS (direct cortical stimulation): current instead of magnetic field, invasive used during brain surgeries, non-invasive version tDCS (transcranial direct current stimulation)
- these stimulation techniques used to check if a certain region is causally related to a particular language activity

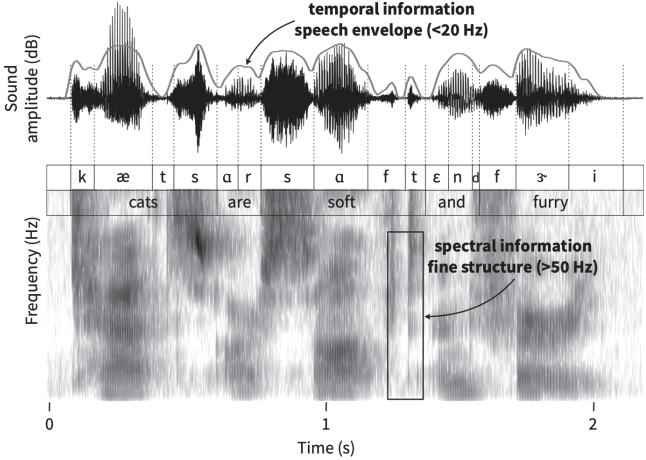
from sounds to words

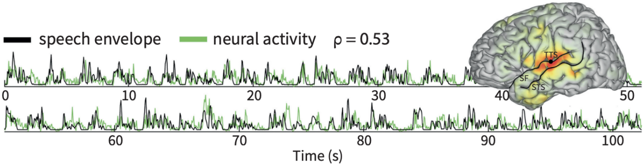
acoustic signal →(1) neuro-auditory representation (*neurogram*) →(2) neuro-phonologcal representation (*phonological sketch*) →(3) lexical item



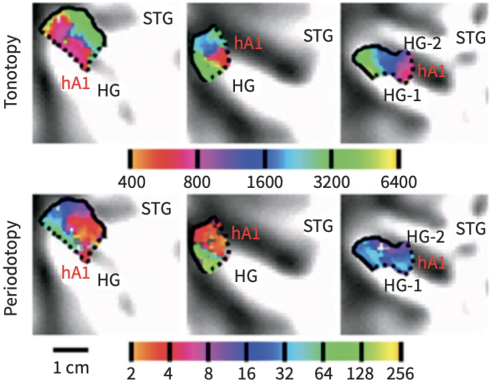
- cochlea: different sites respond to different frequencies, spatial code: cochlea's spectrogram
- cochleagram: neural responses that represent sound
- pass through subcortical structures and arrive at Heschl's gyrus in the primary auditory cortex (in contra-lateral hemisphere)

- tonotopy: cortical spatial code for sound
- different parts of auditory cortex responding to different frequencies (receptive fields)
- speech signal: two parts, speech envelope (waveform) and frequencies (fine structure)



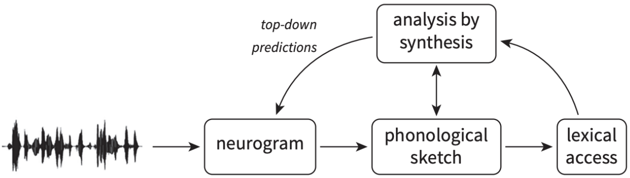


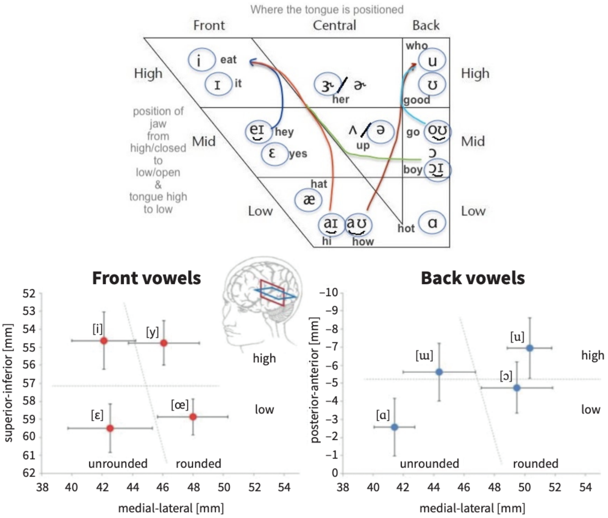
- how is temporal information from speech envelope encoded in the auditory cortex?
- periodotopy: another spatial code that maps the waveform of speech envelope
- two coordinates: sound energy at different frequencies, varying temporal patterns of loudness
- primary auditory cortex has gradient spatial maps for both spectral and temporal information



- continuous variables in tonotopy/perdiodotopy
- passing from this to *discrete* combinatorial information of language
- phonemes are a discrete system
- populations of neurons in the *superior temporal gyrus* have phonemic receptive fields

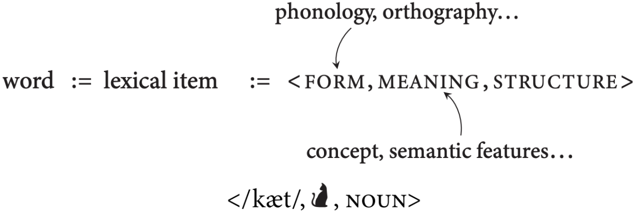
- from the neurogram (tonotopy/perdiodotopy) in the primary auditory cortex a phonological sketch is generated within 100–150 milliseconds in the superior temporal gyrus surrounding the auditory cortex
- integrating information over a short window (for spectral detail) and a longer window (for speech envelope)
- analysis by synthesis: phonological sketch refined through feedback loops between acoustic input and linguistic knowledge
- result is word recognition





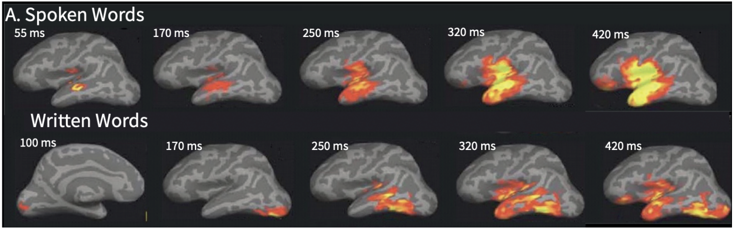
- phonemes of front and back vowels: location of peak of M100 brain response, for front vowels along an inferior-to-superior plane, for back vowels along an anterior-to-posterior plane

Words



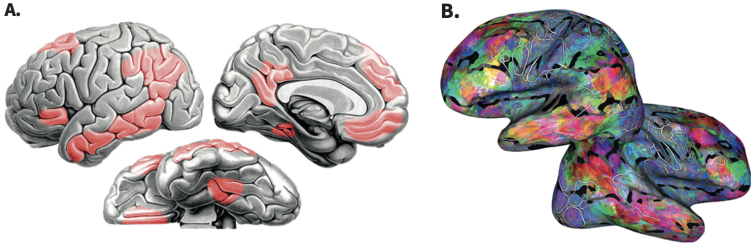
- distinction between words and lexical items
- large but finite set $\mathcal{SO}_0$ of lexical items (meant as form+structure, stem, morphological and syntactic features)
- map $\varphi : \mathcal{SO}_0 \to \mathcal{S}$ to some "semantic space" (association of meaning to words)
- this pairing of form and meaning of words happens in in the *posterior middle temporal gyrus* (pMTG)
- posterior areas of the left temporal lobe linked to semantics (Wernicke: damage affects semantics)

- pMTG damage preserves correct syntax and also preserves semantics (correct assessment of similarity/proximity of concepts) but damages link of semantics to linguistic form
- magnetic fields measured by MEG: brain responses while hearing or reading a single word
- spoken word: primary auditory cortex $\rightarrow$ superior temporal gyrus $\rightarrow$ temporal lobe (pMTG lexical) and anterior areas
- written word: primary visual cortex $\rightarrow$ ventral pathway (visual object recognition) $\rightarrow$ ventral region at border of temporal and occipital lobes (letters, visual word-form area) then pathway merges with spoken word case

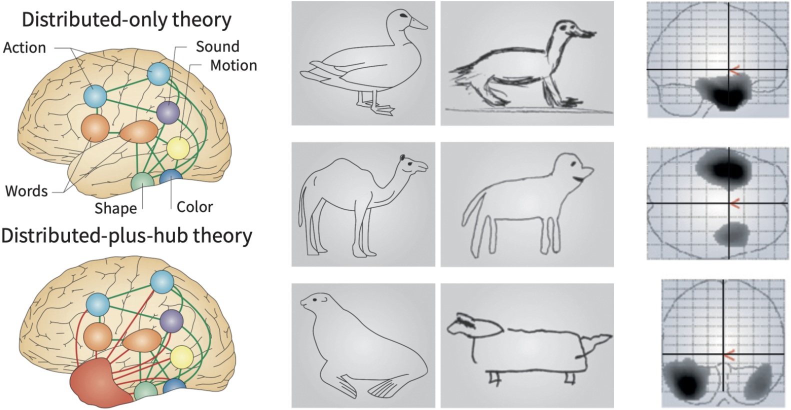


"cats" cat+s	</kæt/, > </s/, PLURAL >	</kæt/, > </s/, PLURAL >
"geese" goose+[plural]	</gus/, > <ø, PLURAL>	</gis/, >
"natural" nature+al	</nætʃɹ/, > </ʌ l/, ADJECTIVE>	</nætʃɹʌ l/, ADJECTIVE-OF- >

- morphemes: basic building blocks of word formation
- full decomposition hypothesis: words are recognized after being decomposed into morphemes



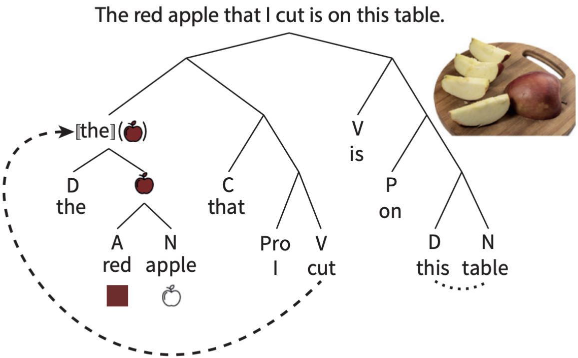
- large parts of the brain working together are involved in semantics: temporal, frontal, and parietal lobes
- wide range of regions activated by words in different classes of meaning (eg red = social words)
- semantics is needed not just for words but for interpretation of visual scenes and other tasks (semantic spaces older than language development), some specialized for words



- for instance *semantic dementia* does not affect only language but visual system too
- anterior temporal lobes are the main site of neural degeneration in semantic dementia

Syntax: the core part of the faculty of language

- sentences are not just strings of words, but hierarchical structures
- two key aspects: structure formation + movement



Theoretical linguistics model (Generative Linguistics)

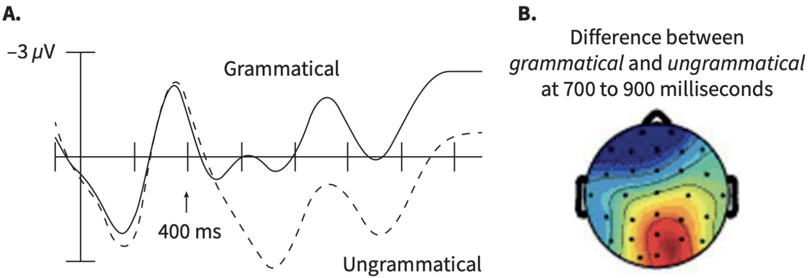
- core computational mechanism (free structure formation and movement)
- system of filters:
  1. grammaticality (phases, theta roles, syntactic parameters, morphology interface)
  2. semantics (plausibility, consistency)
- interface with sensory-motor system

theoretical linguistics model can be formulated mathematically

main question: neuroscience counterparts (instantiation in the neurocomputational architecture of the brain) of all these aspects of the model?

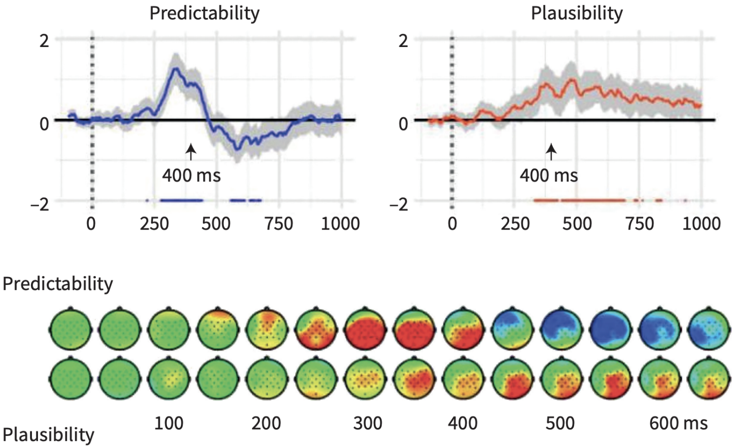
filters: in EEG see two main brain signals event-related potential (ERP) involved in sentence parsing: N400 for semantic acceptability and P600 for syntactic acceptability

Syntax: grammaticality



- P600 strongest over central posterior parts of the scalp, ungrammatical sentences show increased positive response

Semantics: plausibility and predictability

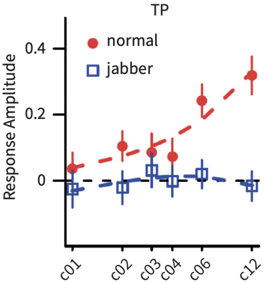


- both predictability and plausibility affect the signal N400, with predictability effect appearing earlier and with larger amplitude

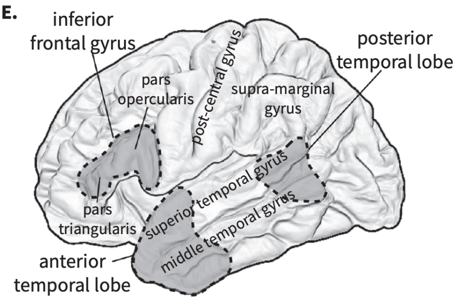
- how to disentangle semantic effects of interpretability predictability from structural constraints of syntax
- Example: Lewis Carroll's "Jabberwocky"

  Twas brillig, and the slithy toves
  Did gyre and gimble in the wabe:
  All mimsy were the borogoves,
  And the mome raths outgrabe

- *left anterior temporal lobe* areas have different response to sentences with real words or syntactically correct sentences with pseudo-words



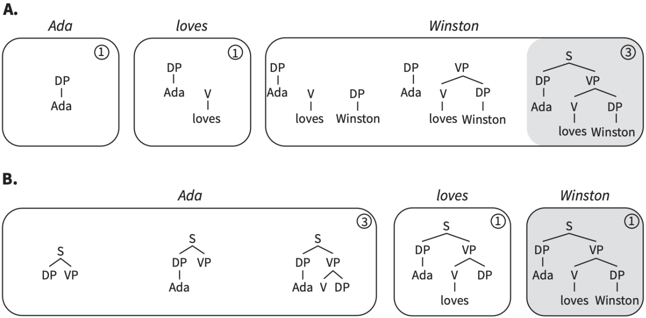
fronto-temporal combinatoric network



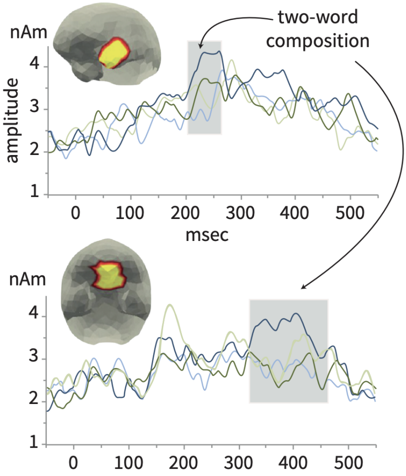
- comparing sentences with unstructured word lists
- left inferior frontal gyrus (LIFG) anterior and posterior temporal regions in sentence understanding
- arcuate fasciculus: white-matter tracts (large bundles of axons) between temporal lobe and inferior frontal lobe
- connecting specific "hot spots" involved in comprehending sentences

compositional process

- bottom-up versus top-down process



- linguistic theory proposes a structure building model that is bottom-up (Merge action on workspaces)

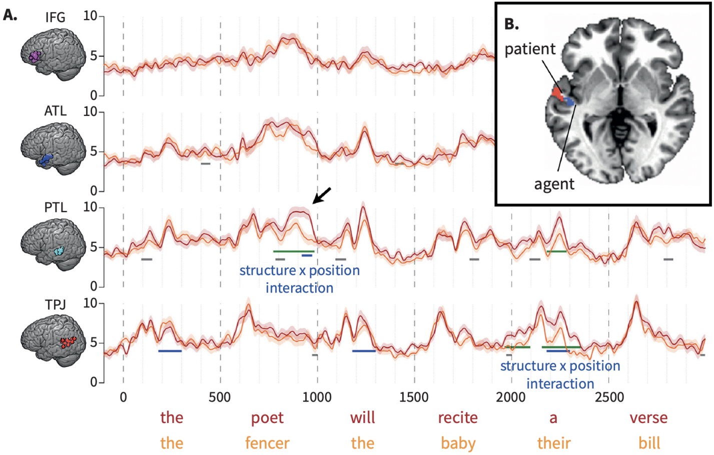


- response to simple 2-word compositions ("red boat") in the left anterior temporal lobe (LATL) at 250 millisec, initial stage of composition, followed by ventro-medial prefrontal cortex (VMPFC) at 400 millisec, later, perhaps semantic, evaluation of composed phrase (syntax-semantics interface)

- but same area LATL also appears involved in both syntactic structure-building and conceptual/semantic aspects interacting: increased activity for structure-building but *if* words in the composition make meaning more specific (restrictive), not if made broader, more general
- role of different sub-regions of LATL?

Syntax in the posterior temporal lobe

- increase in left posterior temporal activity for sentences, compared to phrases
- different parts of the left posterior temporal lobe (LPTL) encode thematic roles (theta theory) like agent/patient (external argument, internal argument)



Dependencies

- left inferior frontal gyrus (LIFG) involved in sentence processing
- original idea (Broca, Wernicke) of comprehension versus production is more subtle in modern understanding
- in linguistic theory the same mechanism that is responsible for sentence building also acts for sentence parsing
- non-fluent Broca's aphasia is now also understood to be a comprehension problem not just a production problem
- Example: passivization

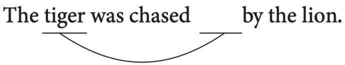
a. The deer was chased by the lion

b. The tiger was chased by the lion

issues when "semantically reversible" (so syntax is affected)

Dependencies and movement

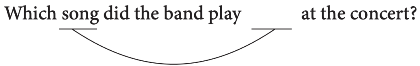
- in the structure formation process for syntax, long distance dependencies are typically introduced by *movement* (transformations)



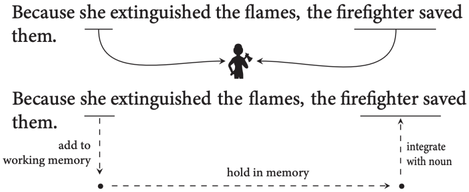
- large studies of stroke patients with patterns of lesion overlap, and neurodegenerative disorders affecting language-related brain regions (measurements of thickness of the cortical gray matter)
- reduced gray matter in the inferior frontal gyrus affects complex semantically reversible sentences

different kinds of long distance dependencies in syntax

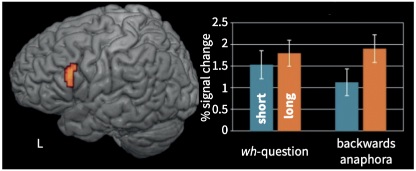
- example: *wh*-movement

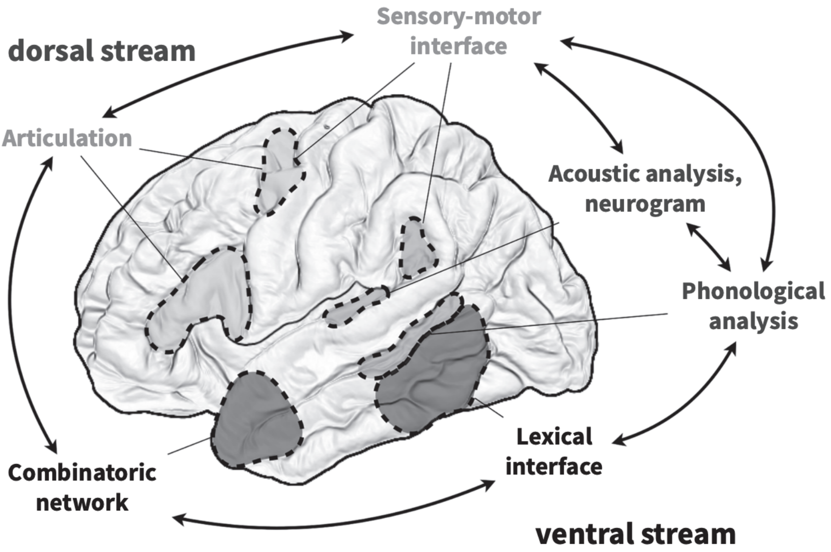


- example: anaphora (and backward anaphora)



- longer dependencies: more demand on working memory... shown in activation of pars triangularis part of LIFG





dorsal stream
Sensory-motor
interface
Articulation
Acoustic analysis,
neurogram
Phonological
analysis
Lexical
interface
Combinatoric
network
ventral stream