Brain basis of composition
Syntax

- The study of how words are combined into sentences.
  - How to characterize the native speaker’s knowledge of what constitutes of well-formed, grammatical, expression in their language?

- Grammaticality ≠ Whether the sentence makes sense
  - Well-formed but nonsensical:
    - Colorless green ideas sleep furiously.
  - Ill-formed but perfectly interpretable:
    - I put the sweater on.
    - I put on the sweater
    - I put it on.
    - *I put on it.
How to study the internal structure of sentences?

Core observation:

- The order of words in sentences can be permuted in various ways.

- But the grammar always treats certain combinations of words as units.

- These units are called constituents.

- The native speaker’s knowledge of how constituents combine with each other is described in phrase structure rules.
Discovering constituency

The boys ate **burgers and fries**.

What did the boys eat _? Burgers and fries.

*What did the boys eat _ and fries? Burgers
Burgers and fries the boys ate _.

*Burgers and the boys ate _ fries.

*Burgers the boys ate _ and fries. (bad with a flat intonation)
Aspects of syntax

- Syntactic realization of event participants (who did what to whom?)
  - The mouse chased the cat.
  - The cat was chased by the mouse.

- Agreement
  - These mice are cat-chasers.
  - *These mice is cat-chasers.
  - These mouse are cat-chasers.

- Case
  - I saw him. (accusative object)
  - I saw he*.

- Displacement
  - the senator who the reporter attacked _ quit.
In order to find syntax in the brain, what should we look for?

- What are the real-time processes that serve to build syntactic structures?
  
  *Minimally:*
  - Composition.

- Establishing dependencies between the surface position in which a constituent occurs and the site where it is interpreted.

Object relative: *the senator* who the reporter attacked _ quit.
Subject relative: *the senator* who _ attacked the reporter quit.
In order to find syntax in the brain, what should we look for?

- Case and agreement

1. John saw him. vs.
2. *John saw he. (case violation)

3. Look how interesting this paper is. vs.
4. *Look how interesting these papers is. (agreement violation)
Typical contrasts of functional imaging studies

- List of words vs. sentences.
  - Goal: to find neural correlates of composition
  - A gross contrast, varies *everything* that distinguishes words from sentences.

- Hard vs. easy syntax.
  - Goal is to control for semantics while manipulating the difficulty of syntactic processing.
  - Danger/issue: hard syntax may engage different processing mechanisms from easy syntax.
The most heated debate:

- The role of Broca’s area in syntactic processing.

- Commonly thought of as the “syntax area” of the brain, partly based on aphasiology.
What google had to say about “syntax in the brain” yesterday (meaning some time last fall):

So what does the evidence look like?
Stromswold et al. (1996): Broca’s area lights up for complex syntax

- A PET study contrasting center-embedded and right-branching structures.
- Center-embedded:
  The juice that the child spilled stained the rug.
- Right branching:
  The child spilled the juice that stained the rug.
A PET study contrasting center-embedded and right-branching structures.

Center-embedded:
*The juice that the child spilled ___ stained the rug.*

Right branching:
*The child spilled the juice that ___ stained the rug.*

Lots of psycholinguistic evidence that center-embedded structures are much harder to comprehend than right-branching structures.

Stromswold et al. (1996): Broca’s area lights up for complex syntax
Complex vs. simple sentences

Stromswold et al., 1996:

Center-embedded:

Right branching

- Blocked design.
Complex vs. simple sentences

Stromswold et al., 1996: Broca’s area

Fig. 2. Statistical parameter map (omnibus subtraction image) showing increased rCBF in the pars opercularis of the left hemisphere during judgments of semantic plausibility of sentences with center-embedded compared to right-branching relative clauses (condition 1 – condition 2).
Broca’s activation due to syntax or…

- Increased working memory demands?
Towards mechanism:
Verbal working memory and articulatory rehearsal

- The decay of phonological information can be prevented by continuously articulating it subvocally (Baddeley’s “phonological loop”).

- Hypothesis:
  - Articulatory rehearsal aids the comprehension of syntactically complex sentences.
  - Broca’s area (as a production area) houses the articulatory rehearsal mechanism.
Rogalsky, Matchin & Hickok (2008): Does a secondary task of articulatory rehearsal eliminate a complexity effect in Broca’s area?

Behavioral data: only object relatives significantly worsened by articulatory rehearsal
Rogalsky, Matchin & Hickok (2008): Does a secondary task of articulatory rehearsal suppress a complexity effect in Broca’s area?

- fMRI study: participants judge subject and object relatives for plausibility.
  - Object Relative: The money that the robber stole was in the bank vault.
  - Subject Relative: The robber that stole the money was in the bank vault.
  - Object Relative: #The robber that the money stole was in the bank vault.
  - Subject Relative: #The money that stole the robber was in the bank vault.
Rogalsky, Matchin & Hickok (2008): Does a secondary task of articulatory rehearsal eliminate a complexity effect in Broca’s area?

Original Stromswold result:

- Articulatory rehearsal elevates the activation level of the subject relatives, such as that no OR vs. SR effect is observed. Under this secondary task, Broca’s activity is saturated.
- Evidence for articulatory rehearsal as a possible source of the syntactic “complexity” effect in Broca’s region.
- Does not show though that the LIFG increase for ORs during “no task” is caused by articulatory rehearsal.
Broca’s activation linked to

- “Complexity” as exemplified by long-distance dependencies
- Aspects of working memory

Does Broca’s area “light up” for syntactic composition more generally?

- The hypothesis that it is the “syntax area” of the brain predicts that it should.
Sentences vs. word lists

Localizing components of a complex task: sentence processing and working memory

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Stimuli (visual):

Word lists (containing both open class and closed class items) vs.

sentences
Sentences vs. word lists

- Bilateral anterior temporal lobe activation (superior and middle temporal gyri).
Sentences vs. words

- Sentences activate anterior parts of the temporal lobe either only in the LH or bilaterally.

- Some evidence that precise localization may be modality dependent.

- Broca’s area does not light up for easy syntax in many classic studies, suggesting that it is not a likely locus of composition.
A counterexample
Cortical representation of the constituent structure of sentences

Christophe Pallier\textsuperscript{a,b,c,d,1,2}, Anne-Dominique Devauchelle\textsuperscript{a,c,d,1}, and Stanislas Dehaene\textsuperscript{a,c,d,e,2}

Table 1. The stimuli were 12 items long sequences obtained by concatenating constituents of fixed sizes extracted from natural or jabberwocky right-branching sentences

<table>
<thead>
<tr>
<th>Condition</th>
<th>Constituent size</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>c12</td>
<td>12 words</td>
<td>I believe that you should accept the proposal of your new associate I tosieve that you should begept the tropufal of your tew viroate</td>
</tr>
<tr>
<td>c06</td>
<td>6 words</td>
<td>the mouse that eats our cheese two clients examine this nice couch the cause that rits our treeve fow plients afomine this nice bloch</td>
</tr>
<tr>
<td>c04</td>
<td>4 words</td>
<td>mayor of the city he hates this color they read their names tuyor of the roty he futes this dator they gead their wames</td>
</tr>
<tr>
<td>c03</td>
<td>3 words</td>
<td>solving a problem repair the ceiling he keeps reading will buy some reling a grathem regair the fraping he meeps bouding will doy some</td>
</tr>
<tr>
<td>c02</td>
<td>2 words</td>
<td>looking ahead important task who dies his dog few holes they write troking ahead omirpant fran who mies his gog few biles they grite</td>
</tr>
<tr>
<td>c01</td>
<td>1 word</td>
<td>thing very tree where of watching copy tensed they states heart plus thang very gree where of wurthing napy gunsed they otes blart trus</td>
</tr>
</tbody>
</table>

In jabberwocky, all content words were replaced with pseudowords (italics). Examples are only illustrative, because the original stimuli were in French.
Cortical representation of the constituent structure of sentences

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Fig. 2. Brain regions showing a significant increase in activation with constituent size. (A) fMRI results from the normal-prose group who read sequences with actual French words (group analysis thresholded at $T > 4.5$, $P < 0.05$ FWE, spatial extent $> 10$). (B) Areas in blue show a significant constituent size effect in the jabberwacky group listening to delexicalized stimuli, whereas regions in red show a significant group by constituent size interaction (reflecting a stronger effect of constituent size in normal prose than in jabberwacky) (maps thresholded at $T > 3.2$, $P < 0.001$ uncorrected, spatial extent $> 50$). (C) Amplitude of activations across conditions in the six regions of interest (error bars represent $\pm 1$ SEM). Conditions c01 to c12 are organized according to a logarithmic scale of constituent size, thus a line on this graph indicates a logarithmic increase of activation. The fitting lines are from a regression analysis including linear and logarithmic predictors.
The role of Broca’s area in basic syntactic composition is not settled, though the evidence weighs heavily towards a lack of involvement.
Interim summary

• When a full sentence is contrasted with a list of words, the left anterior temporal lobe is most consistently activated.
  – Since the contrast is so gross, this effect could reflect almost any aspect of sentence processing.
• The left inferior frontal gyrus is rather consistently activated by long-distance dependencies
  – The extent to which this reflects any aspect of syntax is unclear. It could reflect basic memory mechanisms.
What we still don’t know on the basis of this literature

• How our brains execute the most basic combinatory operations of language.
Simple composition

In reading

(Bemis & Pylkkänen, *J Neurosci.* 2011)
Auditory Production

- Assuming that comprehension and production employ the same syntactic and semantic combinatory machinery, these effects in the LATL and vmPFC should also emerge during noun phrase production.

- So far, almost nothing is known about the brain bases of syntactic and semantic combinatory operations during production, for two reasons:
  - Hard to get subjects to produce specific utterances of experimental interest
  - The motion artifacts created by mouth movement wipe out most brain data.

- However, semantic and syntactic encoding of short productions such as two-word noun phrases is completed before articulation begins (Alario et al. 2002; Meyer, 1996; Schriefers et al. 1999).

- Thus the millisecond temporal resolution of MEG allows us to measure these planning stages before the onset of motion artifacts.
Auditory Production

These processing stages can be studied millisecond by millisecond with a technique like MEG or EEG.

At this point motion artifacts ruin the electrophysiological signal.

http://www.waseda.jp/wias/researchers/monthly/spot_r_verdonschot.html
The most influential model of language production: Levelt 1999

“lemma” = the word in a syntactic and semantic sense (minus phonology)

“lexeme” = the actual phonological form of the word

[Note that linguists do not use the lemma/lexeme terminology but just talk about morphemes which map meanings to forms]
Auditory Production

A Production Task: Say the phrase or list

- red tree
- green star
- red, blue
- green, brown

400ms until speech 1200ms 400ms until speech 1200ms 400ms

B View Task: Identify the gradients

400ms 300ms 1400ms 300ms 1400ms 300ms 1400ms

(Pylkkänen, Bemis, & Blanco Elorrieta, 2014)
1. LATL & vmPFC in reading and auditory production

ROI results

(Pylkkänen, Bemis, & Blanco Elorrieta, 2014)
Simple composition

In reading

**Composition Task**

<table>
<thead>
<tr>
<th>Two words</th>
<th>One word</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>red</code></td>
<td><code>xkq</code></td>
</tr>
<tr>
<td><code>boat</code></td>
<td><code>boat</code></td>
</tr>
</tbody>
</table>

**List Task**

<table>
<thead>
<tr>
<th>Composition Task</th>
<th>List Task</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>cup</code></td>
<td><code>boat</code></td>
</tr>
<tr>
<td><code>boat</code></td>
<td><code>boat</code></td>
</tr>
</tbody>
</table>

In auditory production

**Visual**

**Auditory**

**Production**

(Pylkkänen et al., 2014, *Cognition*)

(Bemis & Pylkkänen, *J Neurosci.* 2011)
How do these effects extend to other languages?

Let’s change everything, including the articulators
In production,
- composition varied
- while both the visual stimulus and the words uttered stay the same across conditions.
Basic composition in English vs. American Sign Language (ASL)

A) Main effect of phrasal composition

(Blanco Elorrieta, Kastner, Emmorey & Pylkkänen, submitted)
Conclusions

In this body of MEG work:

• Effects of basic composition localize in the left anterior temporal lobe (LATL) and the ventromedial prefrontal cortex (vmPFC).

• In comprehension:
  – The LATL effect peaks at 200-250ms and the vmPFC effect ~400ms.

• In production:
  – The vmPFC effect onsets around 150-200ms and the LATL effect shortly afterwards.

• The fact that the vmPFC effect is late in comprehension and early in production suggests that it may reflect the complex semantic representation that is the end product of comprehension processes and the starting point of production processes.