Imaging Language Processing: Results, Challenges, Prospects

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Guiding ideas in functional neuroimaging of language

Language consists of a set of representations

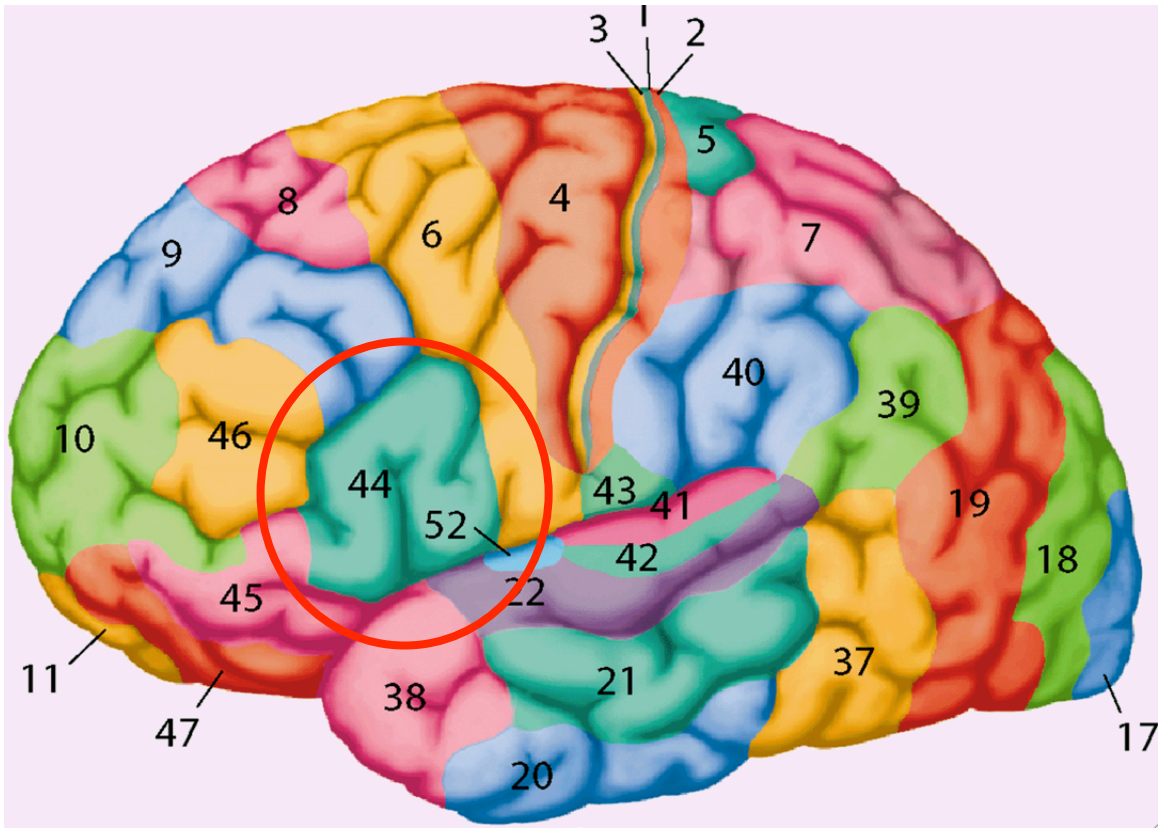
- phonological forms of words
- syntactic structure of sentences
- meanings of words, phrases, sentences

These representations are produced during language production and extracted from the signal by relatively specialized processors

These processors are localized in divisions of neocortex

If this view is correct, the neurobiological challenge is

- to identify the areas of the brain in which operations take place,
- to identify the features of those areas that support particular operations, and
- to relate those features to the expression of genes and environmental factors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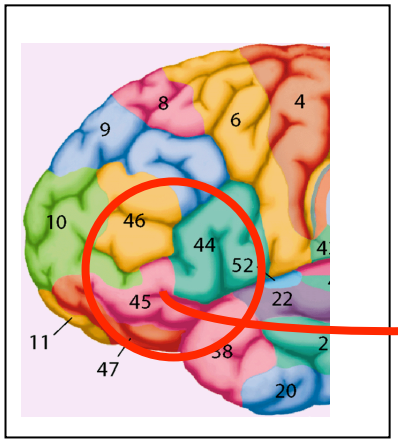
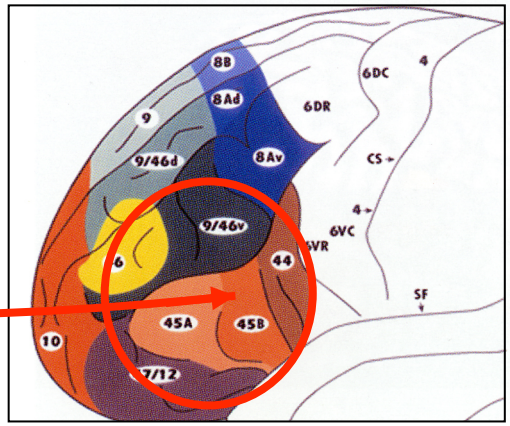
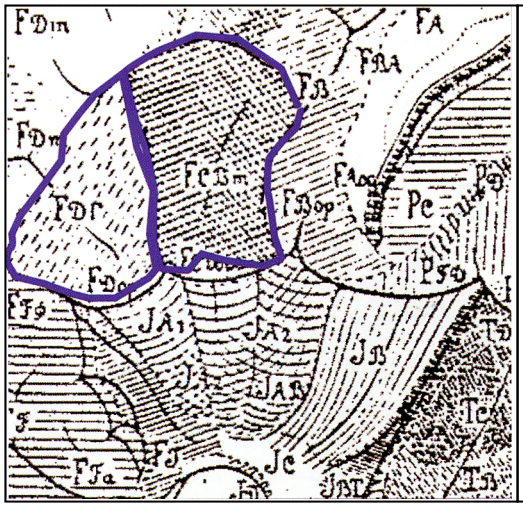
Cytoarchitectonics

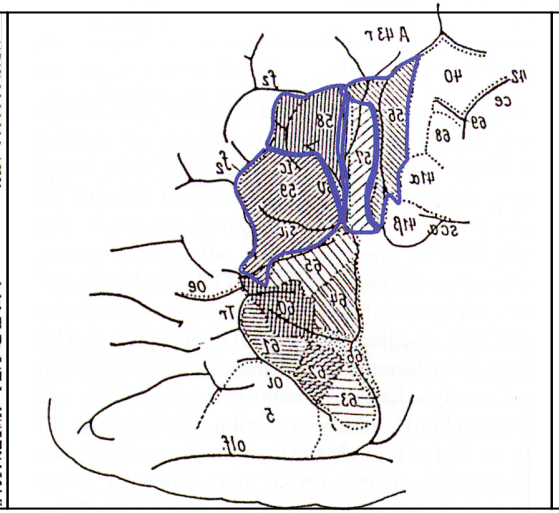


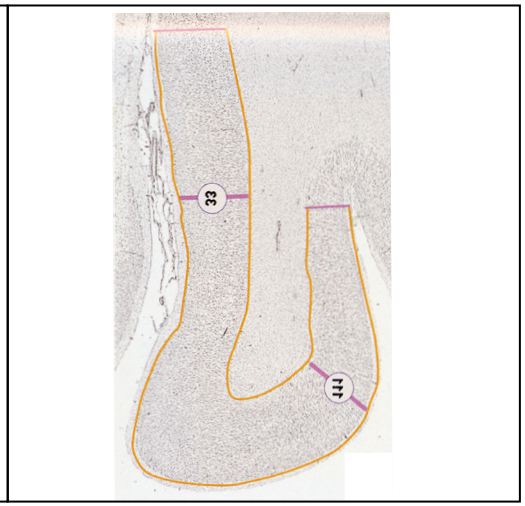


Brodmann

Differentiated Brodmann





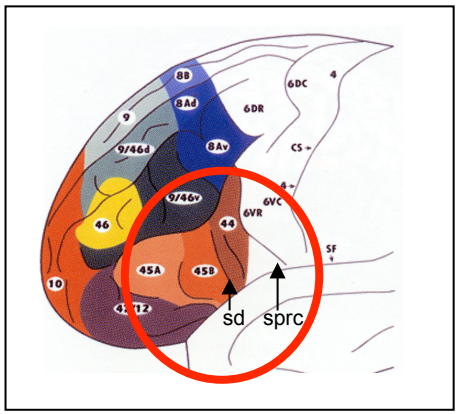


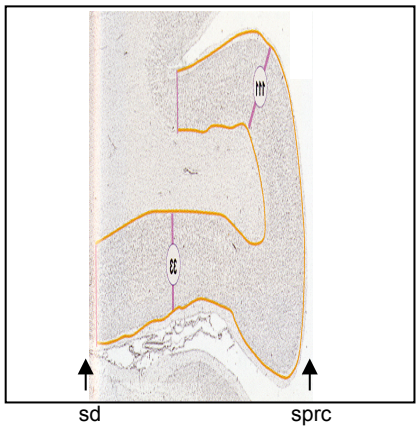
Von Economo and Koskinas

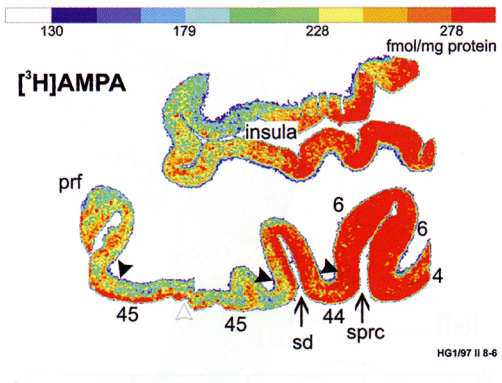
Riegel

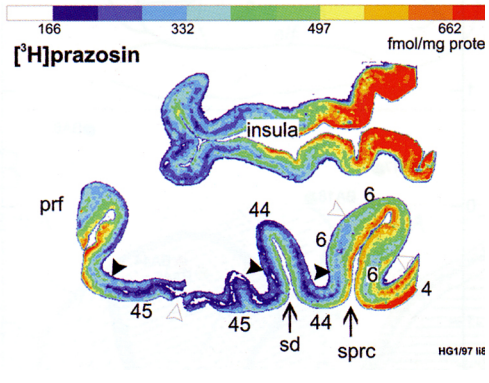
Amunts and Zilles

Receptotonics









Glutamate receptors

Noradrenergic α_1 receptors

Gene Expression in Frontal Cortex

Clustering of 343 genes human mid-gestation

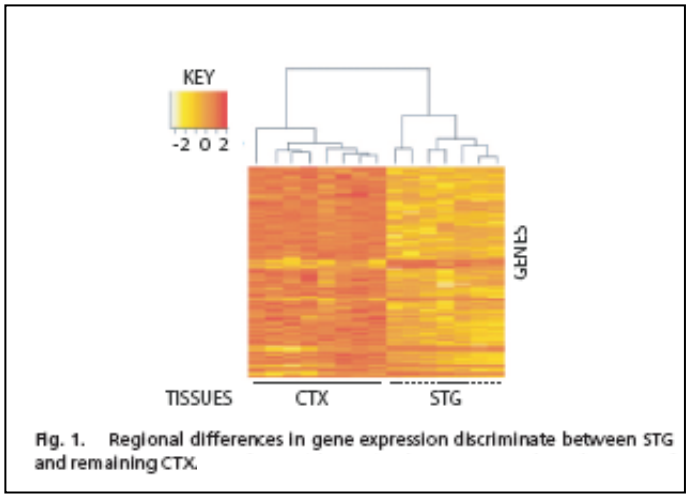
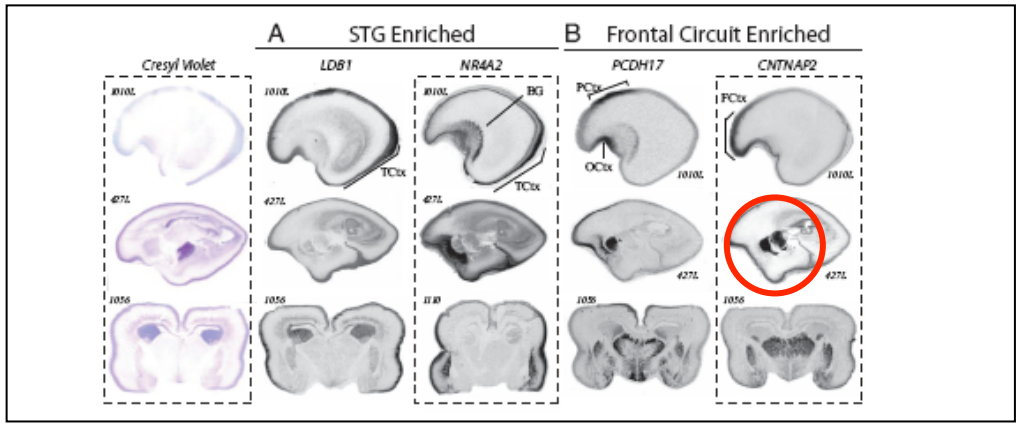
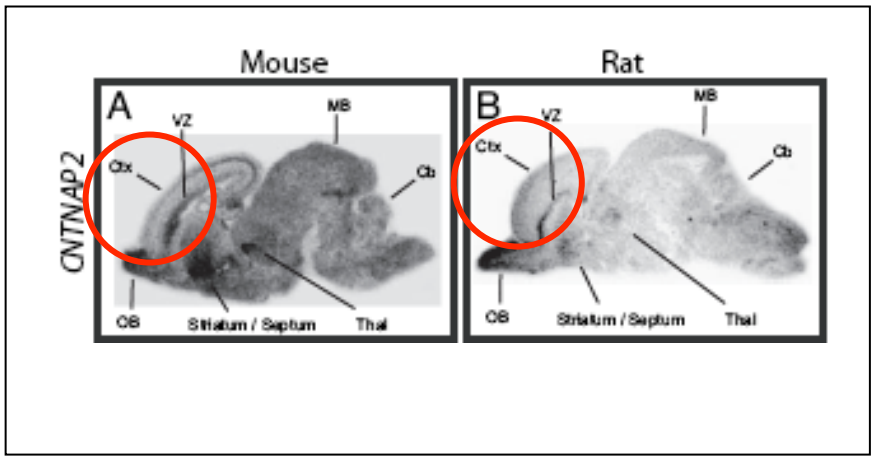


Fig. 1. Regional differences in gene expression discriminate between STG and remaining CTX.

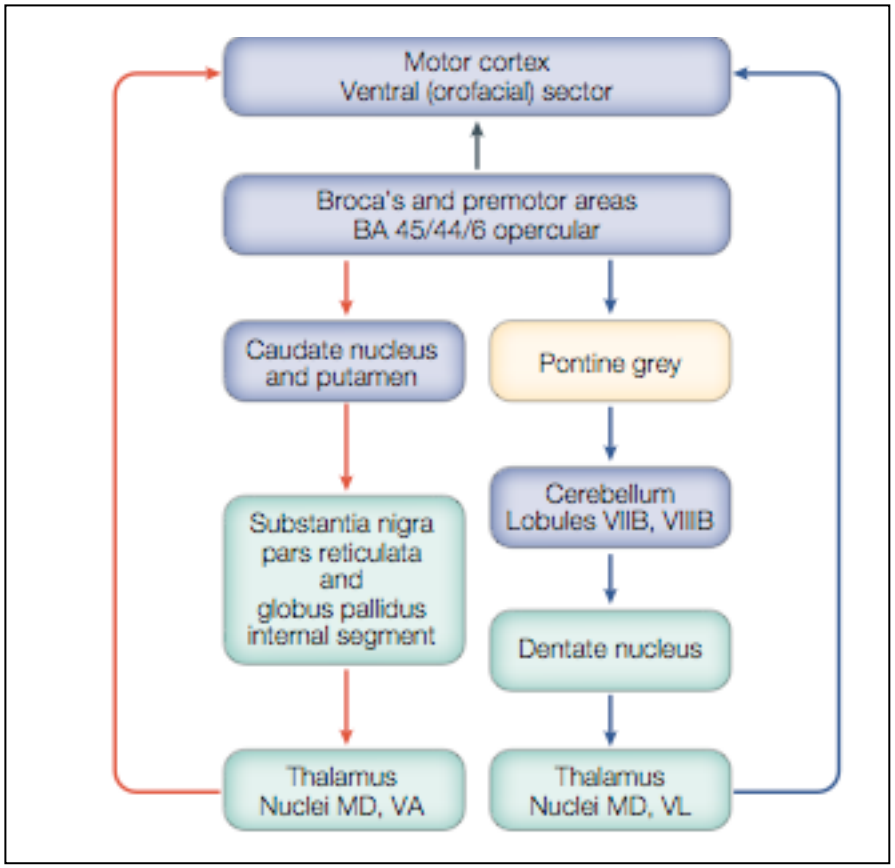
CNTNAP2 in human frontal cortex

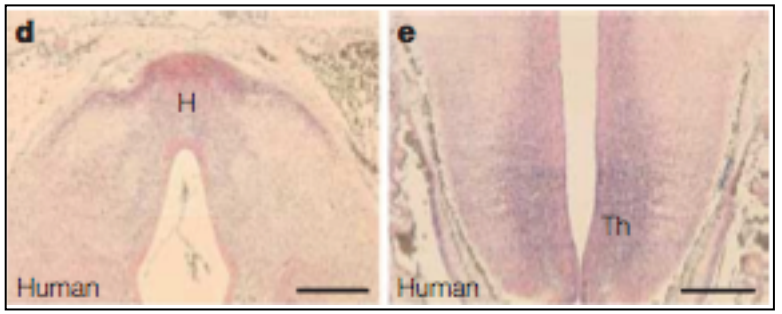


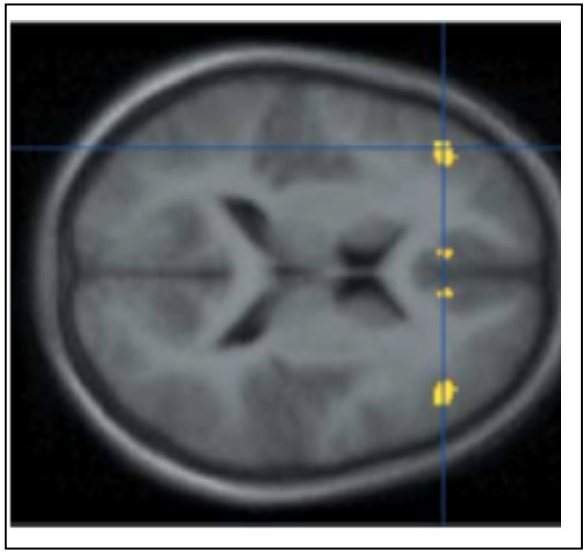
CNTNAP2 in mouse and rat



Gene Expression: FOXP2







These ideas led to a search for neurovascular correlates of particular language-related operations

Phonological features: STG

Word forms: AG

Visual word forms: pITG

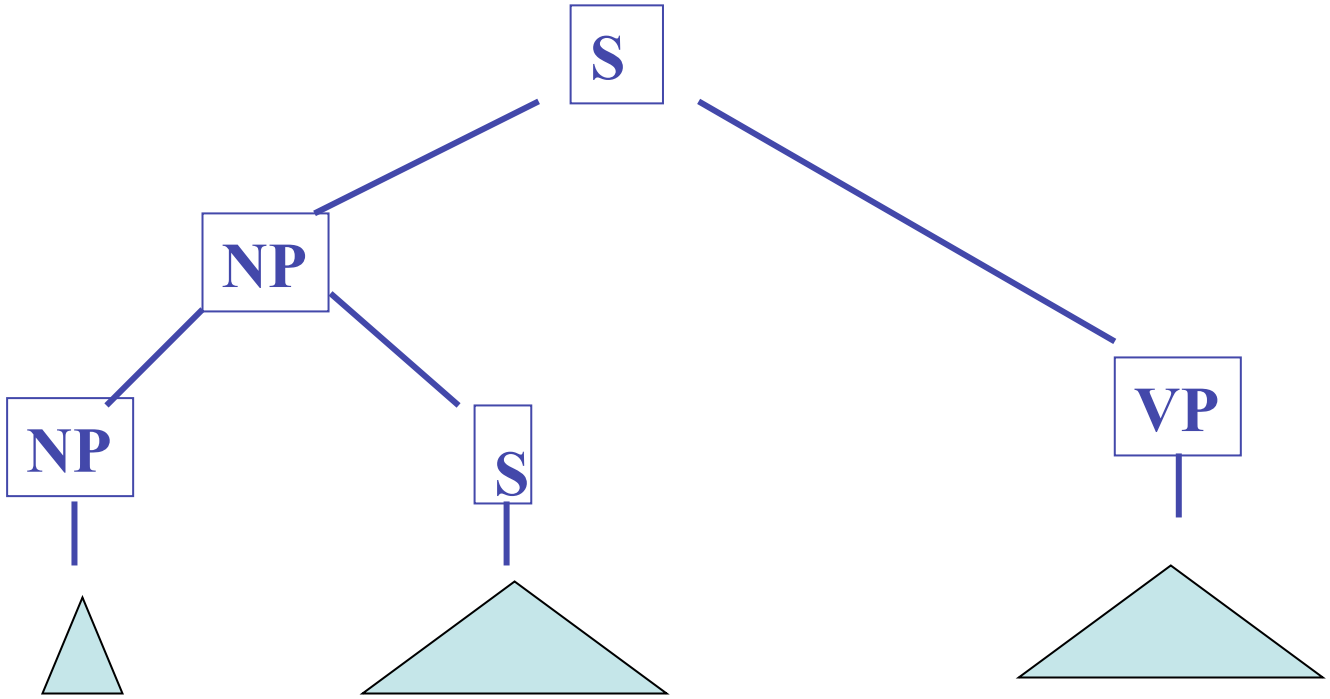
Nominal semantic representations: aITG

Syntactic representations

The boy who chased the girl hugged the baby

The boy who chased the girl hugged the baby

The boy **who chased the girl** hugged the baby



The boy {who chased the girl} hugged the baby

Syntax

Allows for expression of arbitrary relations between items

- The mouse chased the cat

Allows for counterfactual reasoning

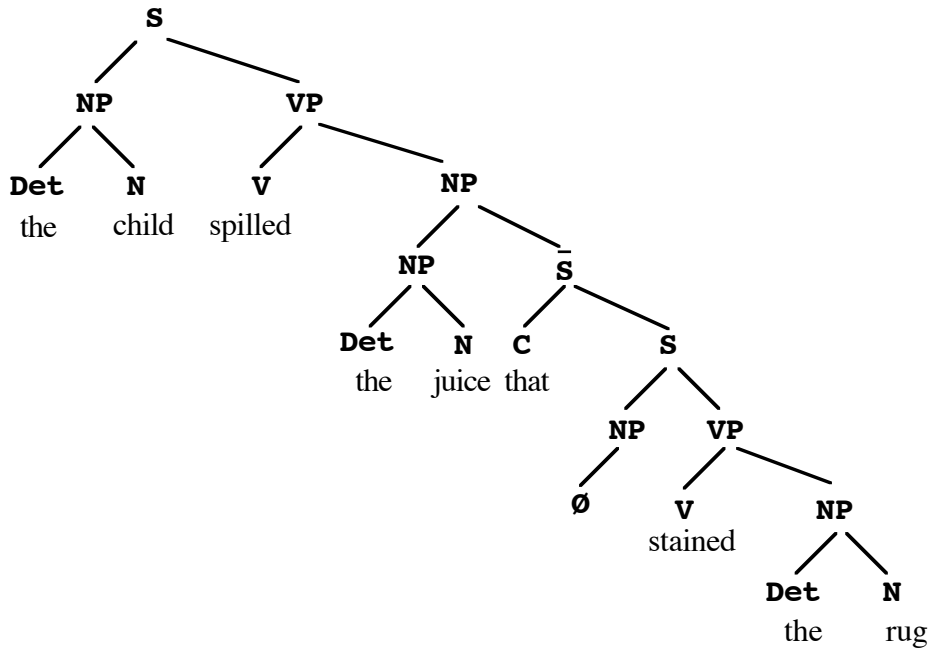
Is of neurobiological interest because of its unique, and uniquely human, structural features

Subject- vs object-extraction

The child spilled the juice that stained the rug.

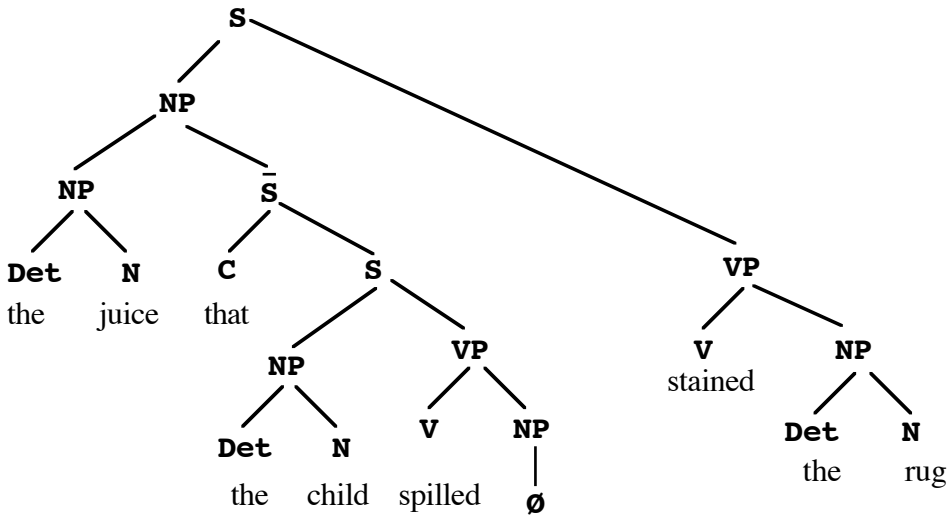
The juice that the child spilled stained the rug.

Subject Extracted Sentence



The child spilled the juice that __ stained the rug.

Object Extracted Sentence



The juice that the child spilled __ stained the rug.

Plausibility Judgment

Subject Extracted

The child spilled the juice that stained the rug.

* The juice spilled the child that stained the rug.

Object Extracted

The juice that the child spilled stained the rug.

* The child that the juice spilled stained the rug.

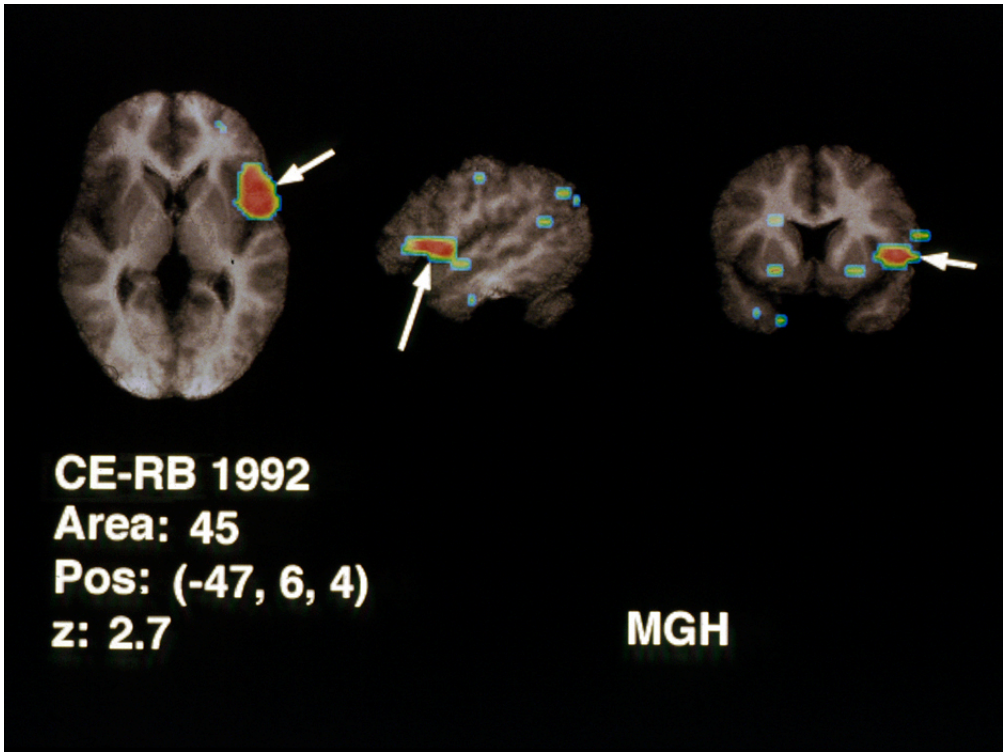
Subjects

- Strongly right-handed
- No first-degree left-handed relatives
- Normal vision and hearing
- No history of neurological or psychiatric disease

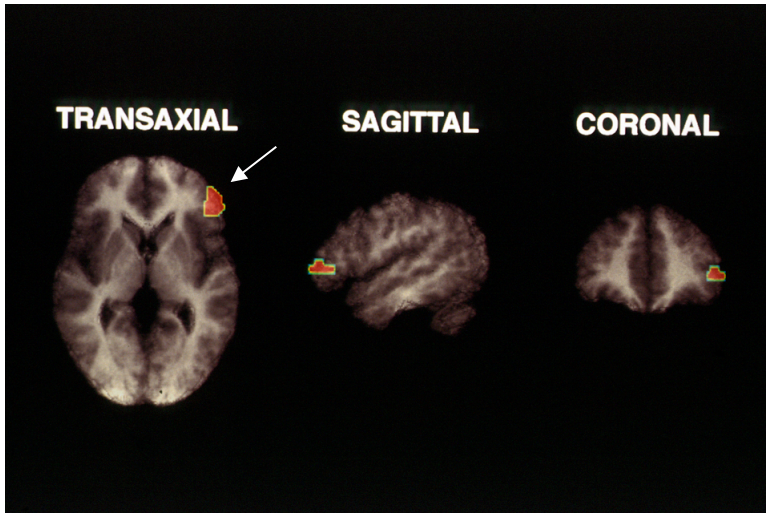
Behavioral Observations

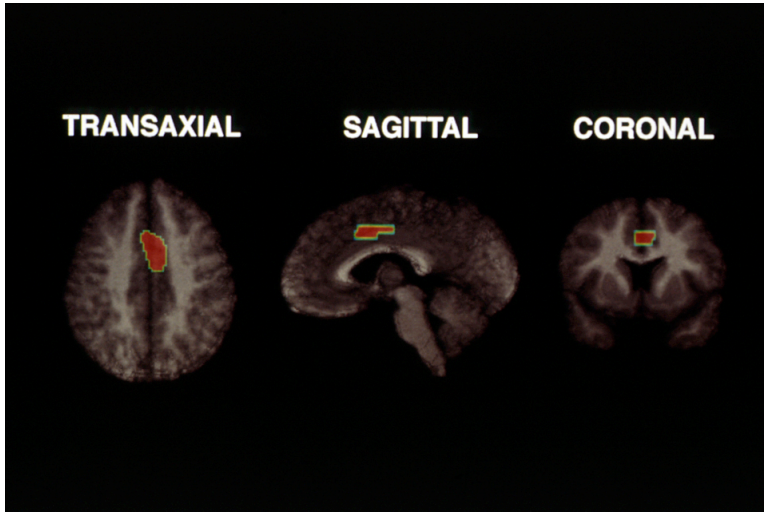
RTs and accuracy measured in scanner show effect of syntactic complexity

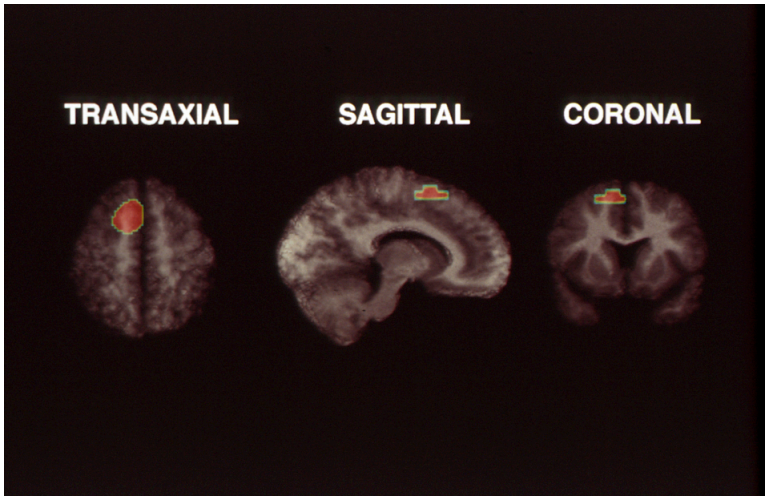
Experiment 1: Visual Presentation, 8 young males



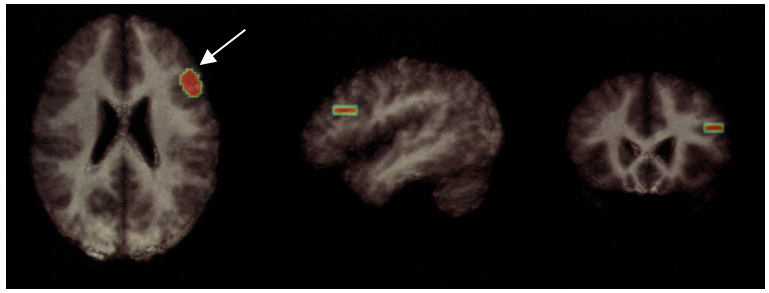
Experiment 2: Visual Presentation, 8 young females

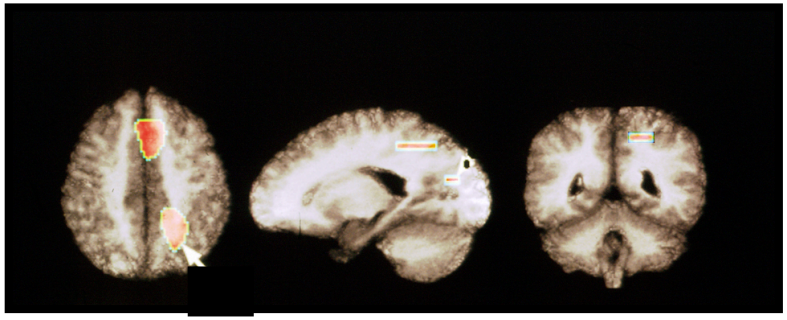




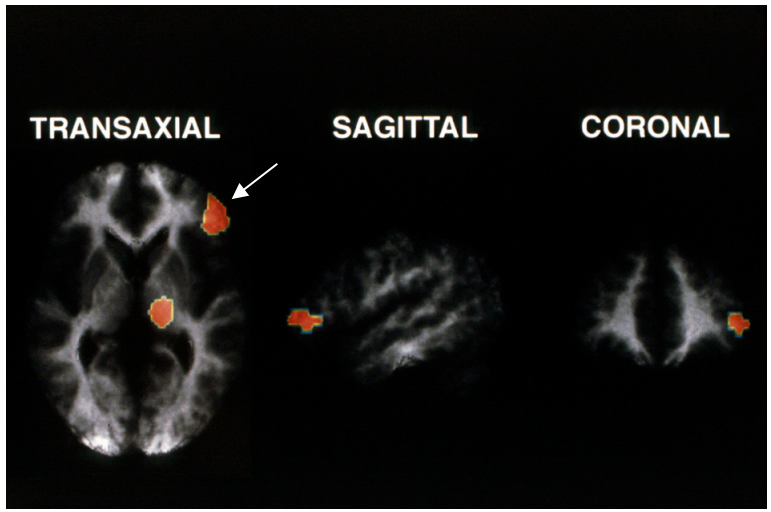


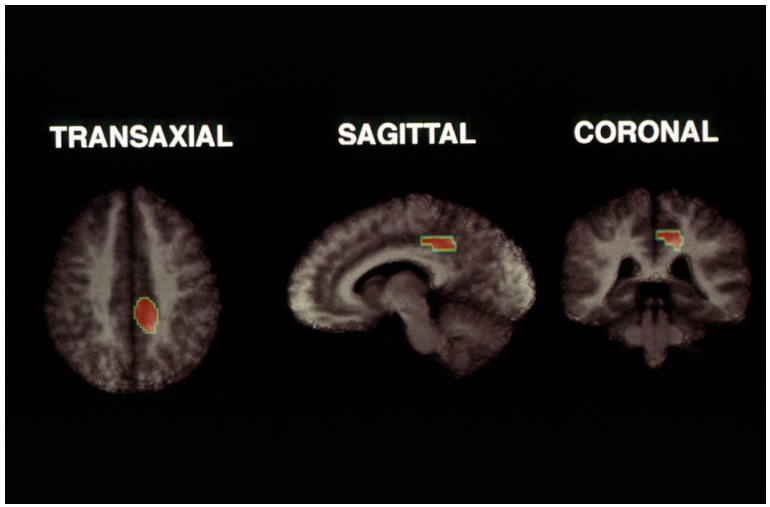
Experiment 3: Auditory Presentation, 16 young subjects

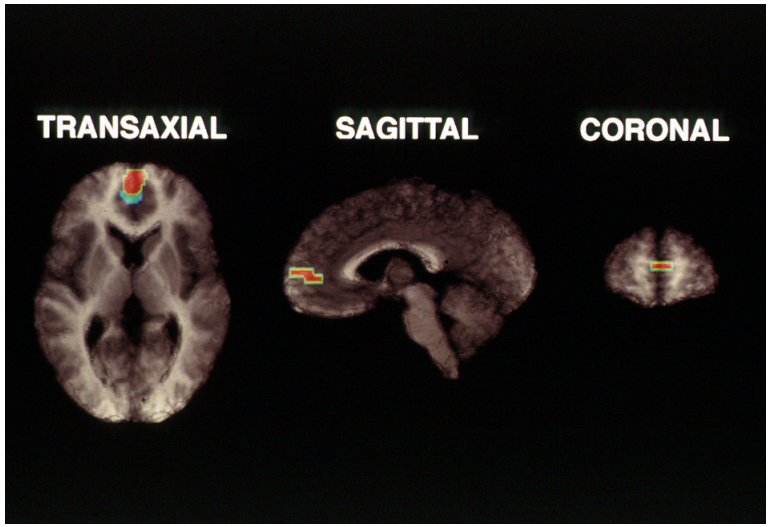




Experiment 4: Written Presentation with Concurrent Articulation, 11 young subjects







Areas of Activation for Subject Object Minus Object Subject Sentences: Young College Educated Students

Experiment	Broca's	Cingulate	Medial Frontal	Sup Parietal	Thalamus
1. 8M	+				
2. 8F	+	+	+		
3. 16 M& F	+		+	+	
4. 6 M& F	+	+	+		+

Conclusion

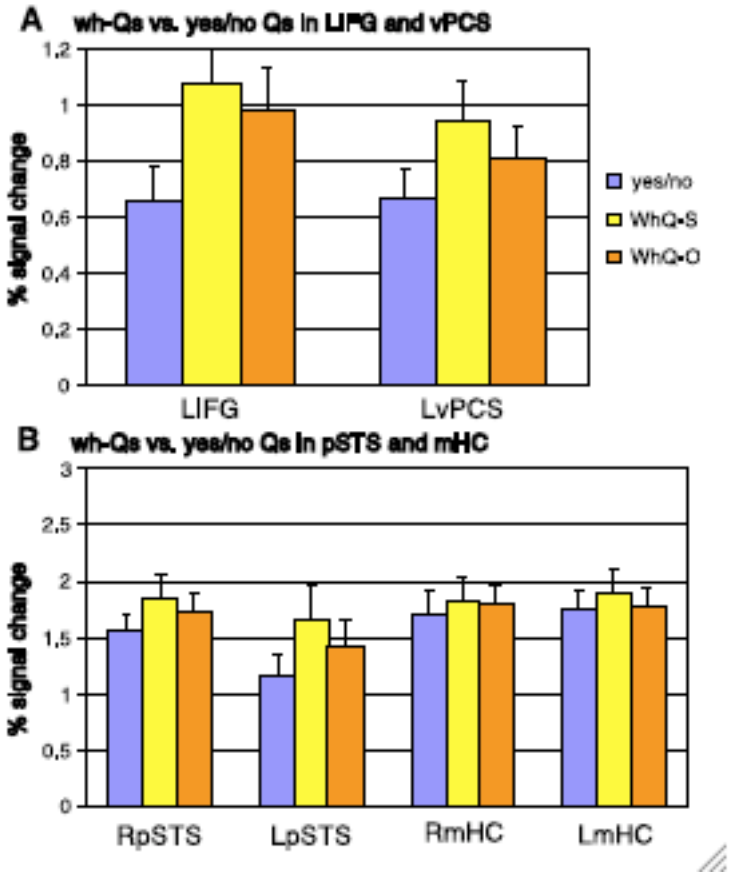
Left IFC responsible for critical aspects of assignment of the structure of object-extracted relative clauses

Conclusion

Left IFC responsible for critical aspects of assignment of the structure of object-extracted relative clauses

BUT OTHER AREAS WERE ACTIVATED

Ben Shachar et al 2004



Syntactic operations are duplicated, distributed, or show indiviudal variability in their neural substrate

- a smaller set of neural features is sufficient for these operations

Some neurovascular activity is due to operations that differ for different sentence types, but are not parsing and interpretation

These are induced by the task factors

Verification

Target (varies in form)

Object Extracted

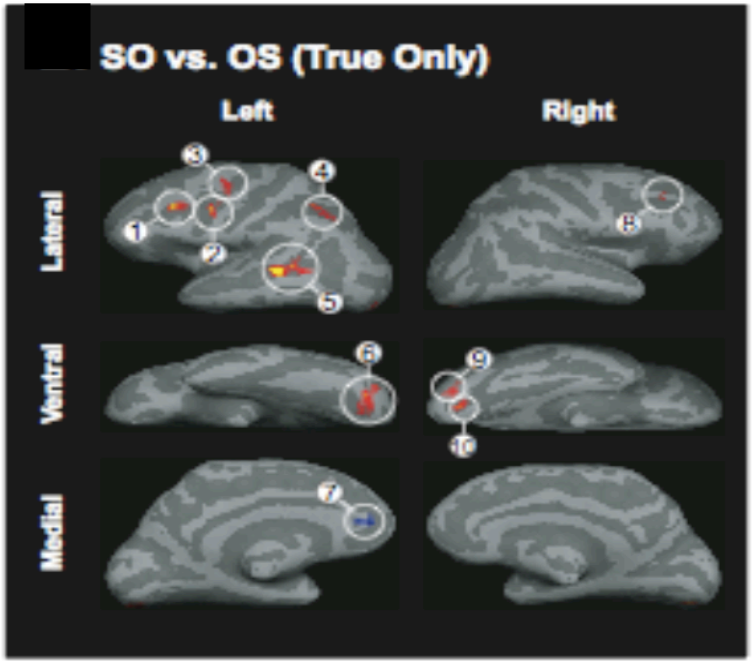
The fireman who the deputy called saved the sailor. (SO)

Subject Extracted

The deputy who called the fireman saved the sailor. (SS)

Probe (simple form)

The fireman saved the sailor


SO vs. OS (True Only)
Left
Right
Lateral
Ventral
Medial
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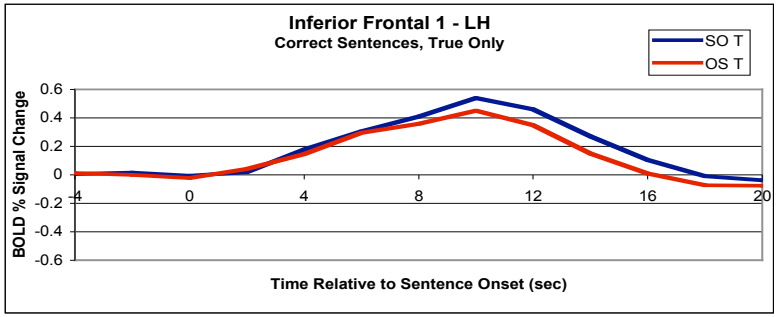
Inferior Frontal 1 - LH
Correct Sentences, True Only
SO T
OS T
BOLD % Signal Change
0.6
0.4
0.2
0
-0.2
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-0.6
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4
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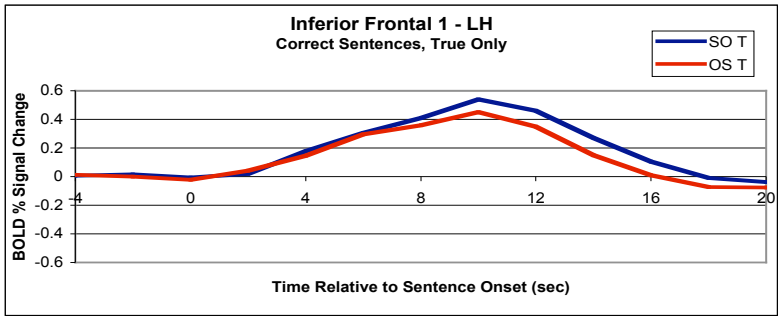
20
Time Relative to Sentence Onset (sec)


Inferior Frontal 1 - LH
Correct Sentences, True Only
SO T
OS T
BOLD % Signal Change
0.6
0.4
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-0.4
-0.6
-4
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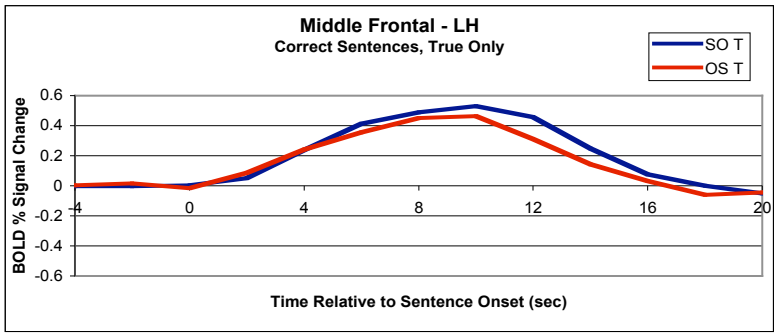
Time Relative to Sentence Onset (sec)


Middle Frontal - LH
Correct Sentences, True Only
SO T
OS T
BOLD % Signal Change
0.6
0.4
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-0.2
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-0.6
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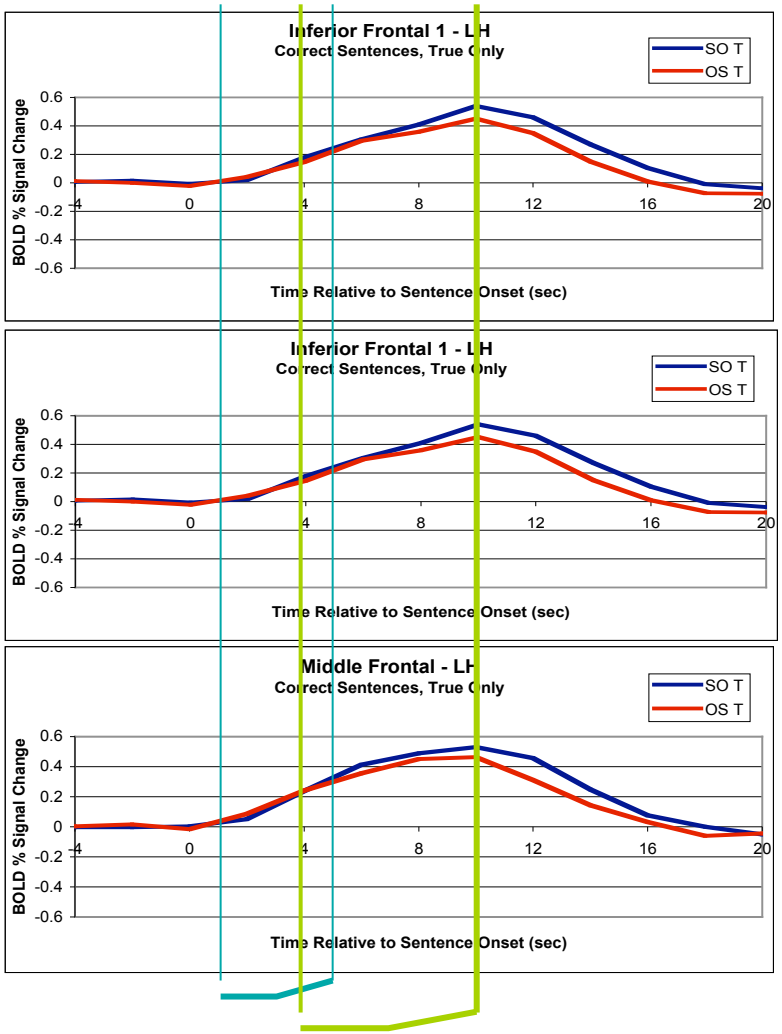
Time Relative to Sentence Onset (sec)


Inferior Frontal 1 - LH
Correct Sentences, True Only
SO T
OS T
BOLD % Signal Change
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Time Relative to Sentence Onset (sec)
Inferior Frontal 1 - LH
Correct Sentences, True Only
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OS T
BOLD % Signal Change
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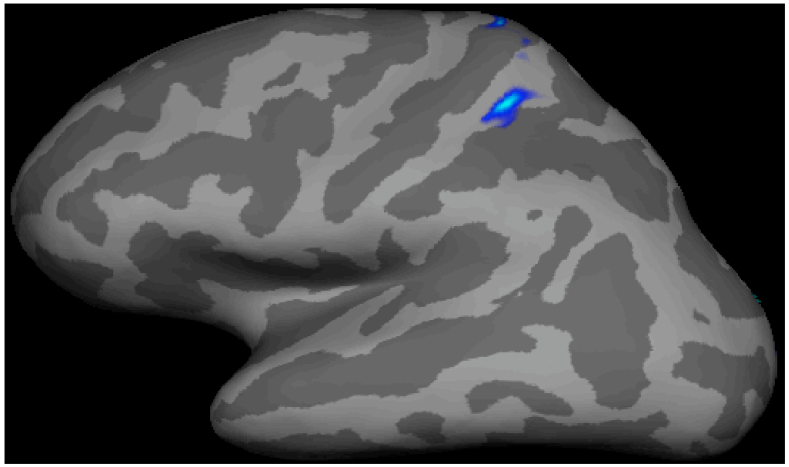
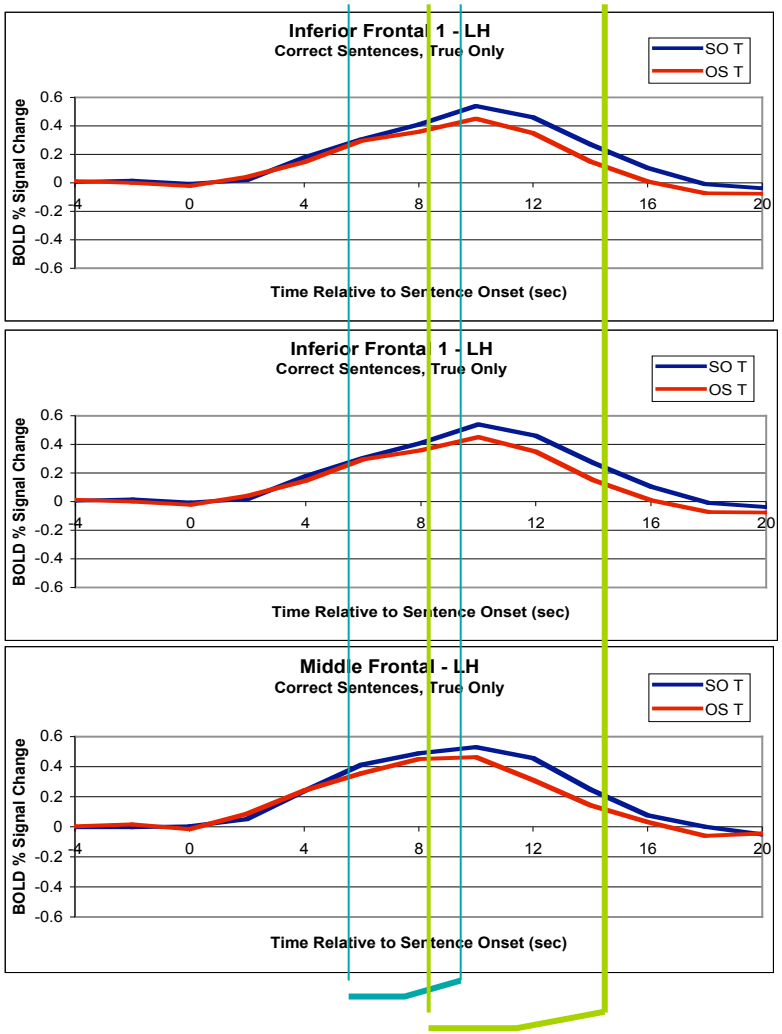
Time Relative to Sentence Onset (sec)

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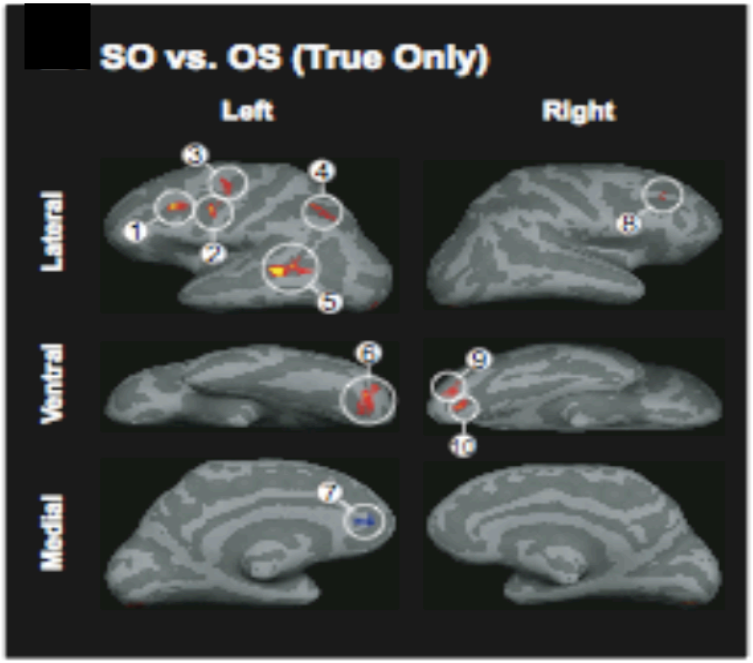
SO vs. OS (True Only)
Left
Right
Lateral
Ventral
Medial
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The BOLD signal effect is NOT due to initial parsing and interpretation

Rehearsal
Reconstruction

These task-related operations occurred after the comprehension process

But they also occur DURING that process.

Study

Same sentences

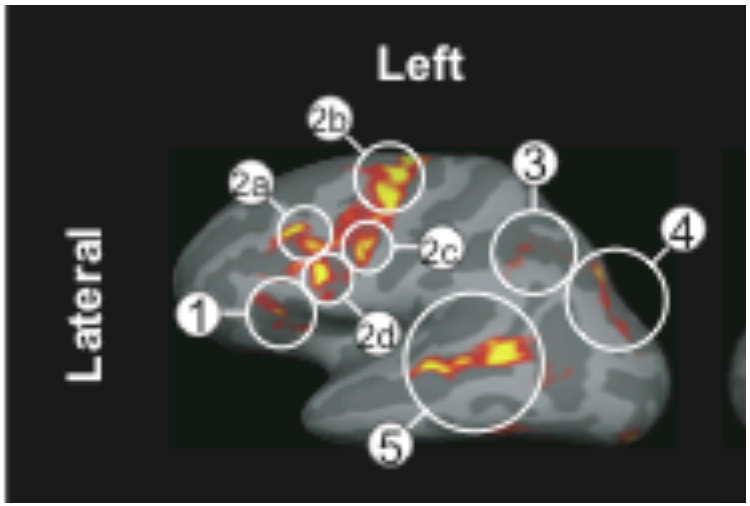
The boy that the rug tripped broke the vase
The rug tripped the boy who broke the vase

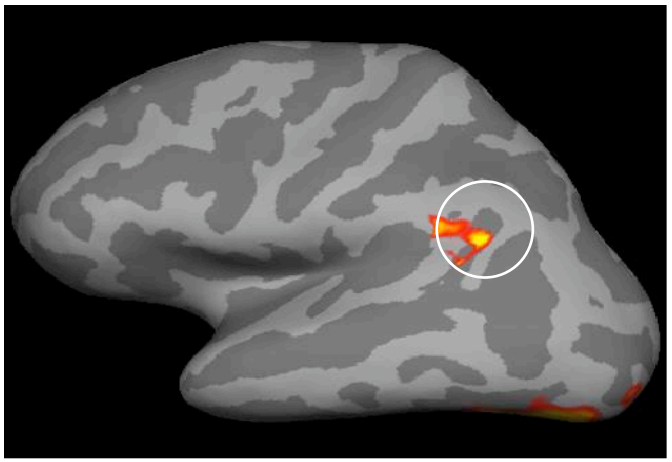
Plausibility judgment

The rug that the boy tripped broke the vase
The boy tripped the rug that broke the vase

Font change detection

The boy that the rug tripped broke the vase
The rug tripped the boy who broke the vase


Left
Lateral
2b
2a
2c
3
4
1
2d
5



Interpretation

Plausibility

- Incremental use of sentence meaning to perform task

Font change detection

- Sentences are processed incidentally
- Sentence structure and meaning are not used to perform the task
- BOLD signal reflects parsing and interpretation

Plausibility Judgment

Object extracted

Unconstrained

The fireman who the deputy called saved the sailor.

Constrained

The policeman who the thief robbed watched the driver.

Subject extracted

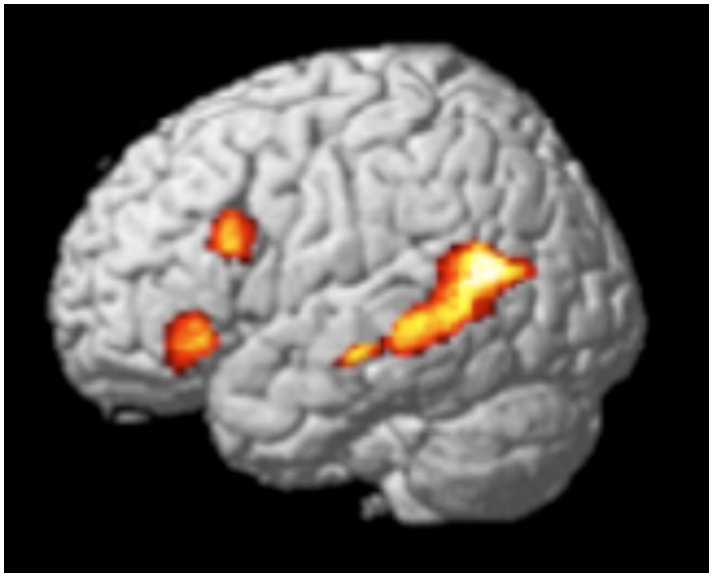
Unconstrained

The fireman who called the deputy saved the sailor.

Constrained

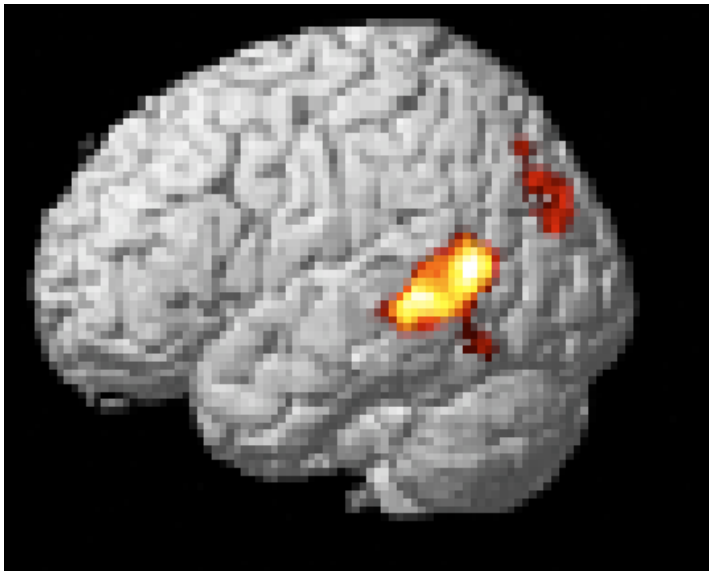
The policeman who arrested the thief watched the driver.

Unconstrained



OE SE OE SE

Constrained



OE SE OE SE

The policeman who the thief robbed watched the driver.

Two routes to meaning:

Syntax -- licensed meaning
Combinatorial -- competitors

Unconstrained:

The fireman who the deputy called saved the sailor.

Both routes --> plausible sentences

Constrained:

The policeman who the thief robbed watched the driver.

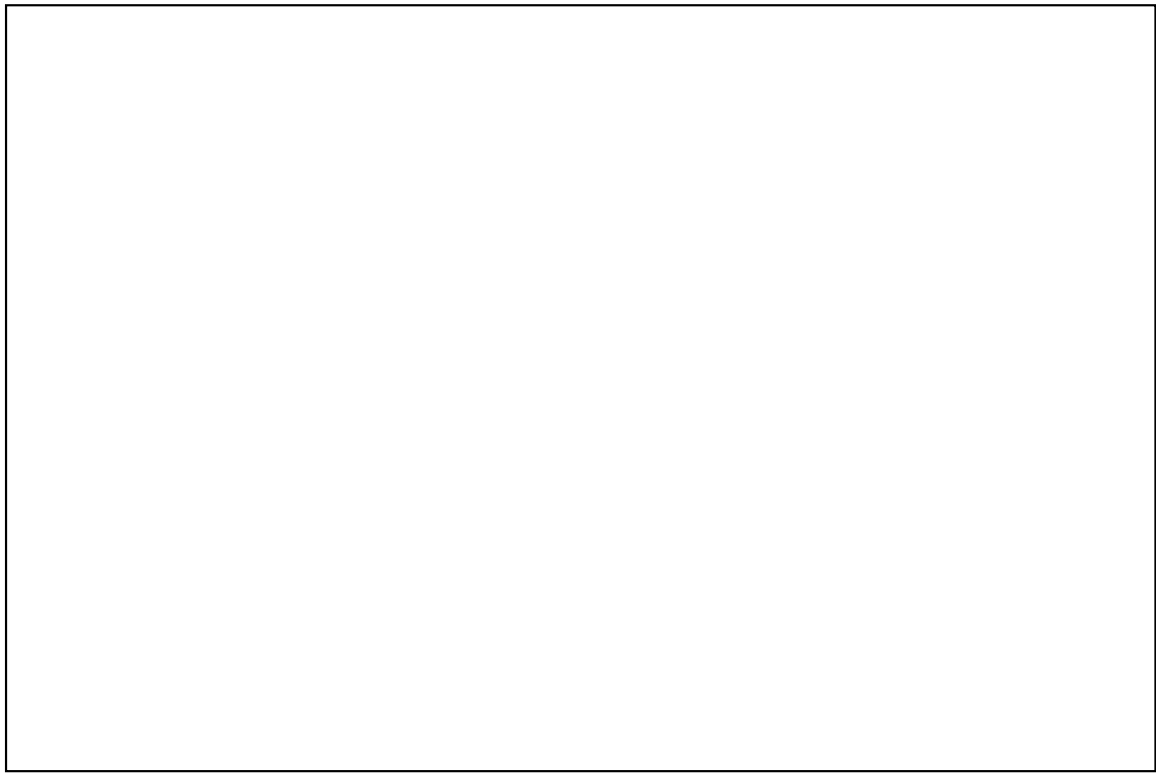
Combinatorial route --> Implausible

Need to check origin of implausible meanings

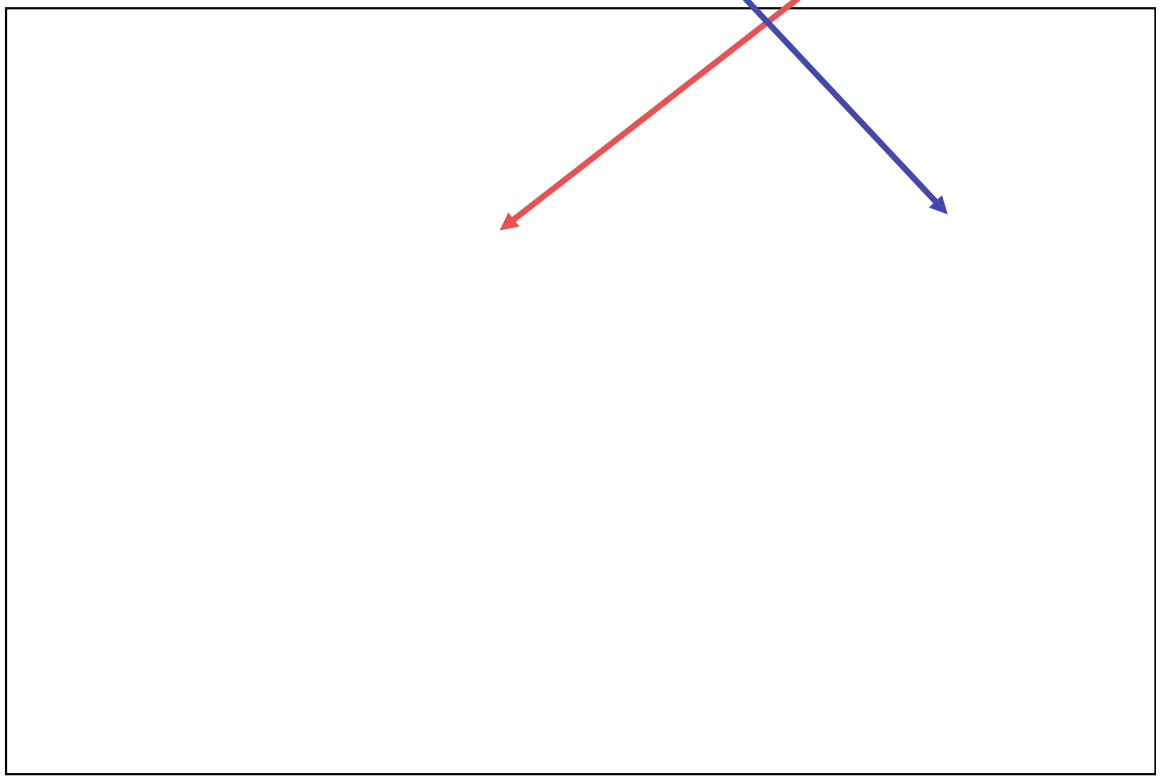
Re-analyze sentence
Compare meaning of re-analyzed sentence against
implausible meaning already computed

Also check meaning of OE unconstrained sentences

	Initial Parse	Second Parse	BOLD signal	Compare	BOLD signal
OE constrained	++	++	++++	+	+
OE unconstrained	++	++	++++	+	+
SE constrained	+	+	++	+	+
SE unconstrained	+		+		



	Initial Parse	Second Parse	BOLD signal	Compare	BOLD signal
OE constrained	++	++	++++	+	+
OE unconstrained	++	++	++++	+	+
SE constrained	+	+	++	+	+
SE unconstrained	+		+		



Conclusions -- same as verification, font change detection:

Some BOLD signal is related to operations associated with the task

Future directions

Examine the functions of the entire network
by considering time course

Time course and causality:
The policeman who the thief ***robbed*** watched the driver.

MTG --> semantic area (ITG) --> MTG --> IFG .

Magnetoencephalography
- millisecond temporal resolution
- good spatial resolution

Granger causality analysis
- causal relations between temporally separated events

Application to sounds of single words

Ganong effect

Perception of intermediate values of acoustic continua affected by lexical status

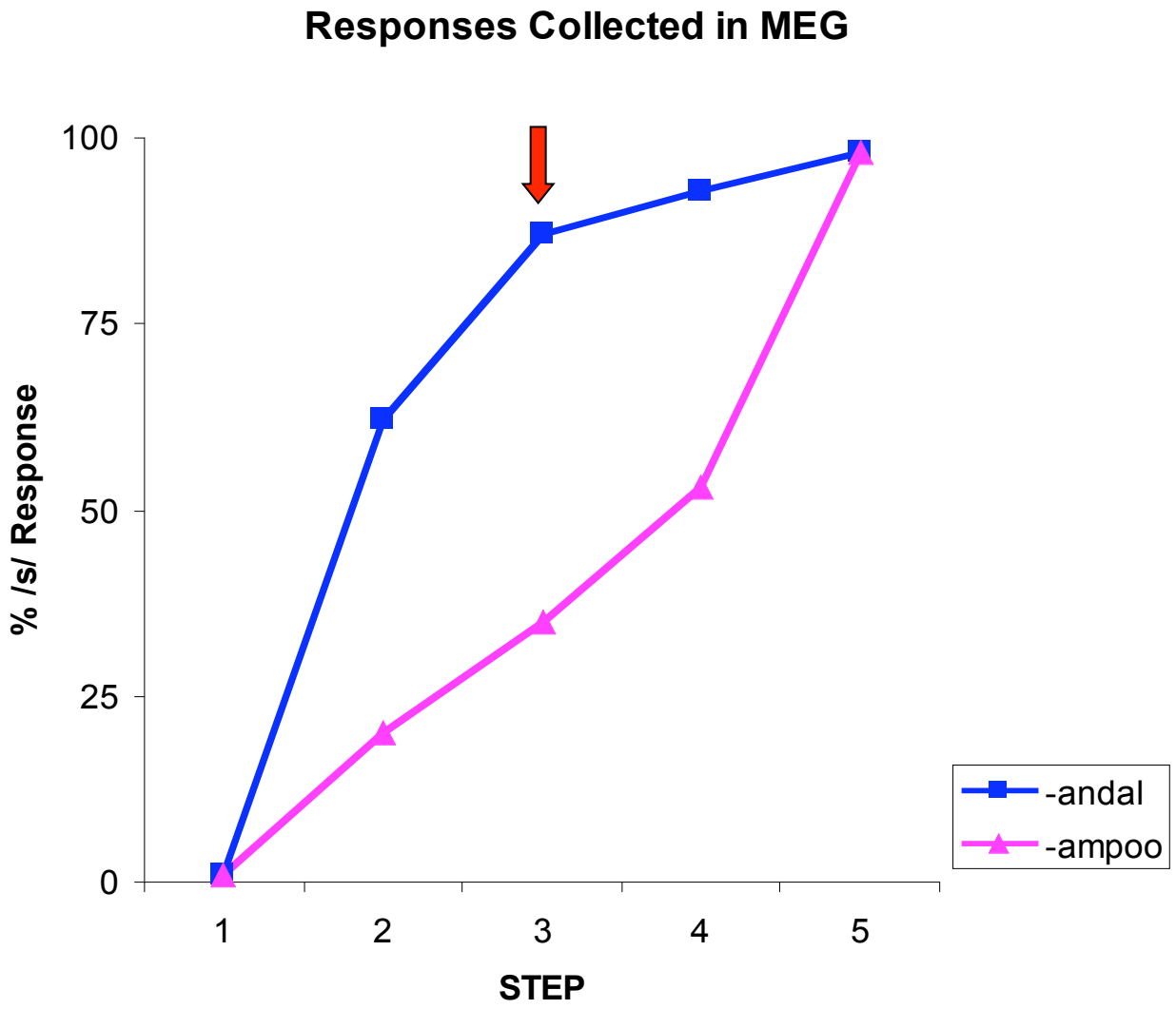
5 step /s/ - /ʃ/ continuum

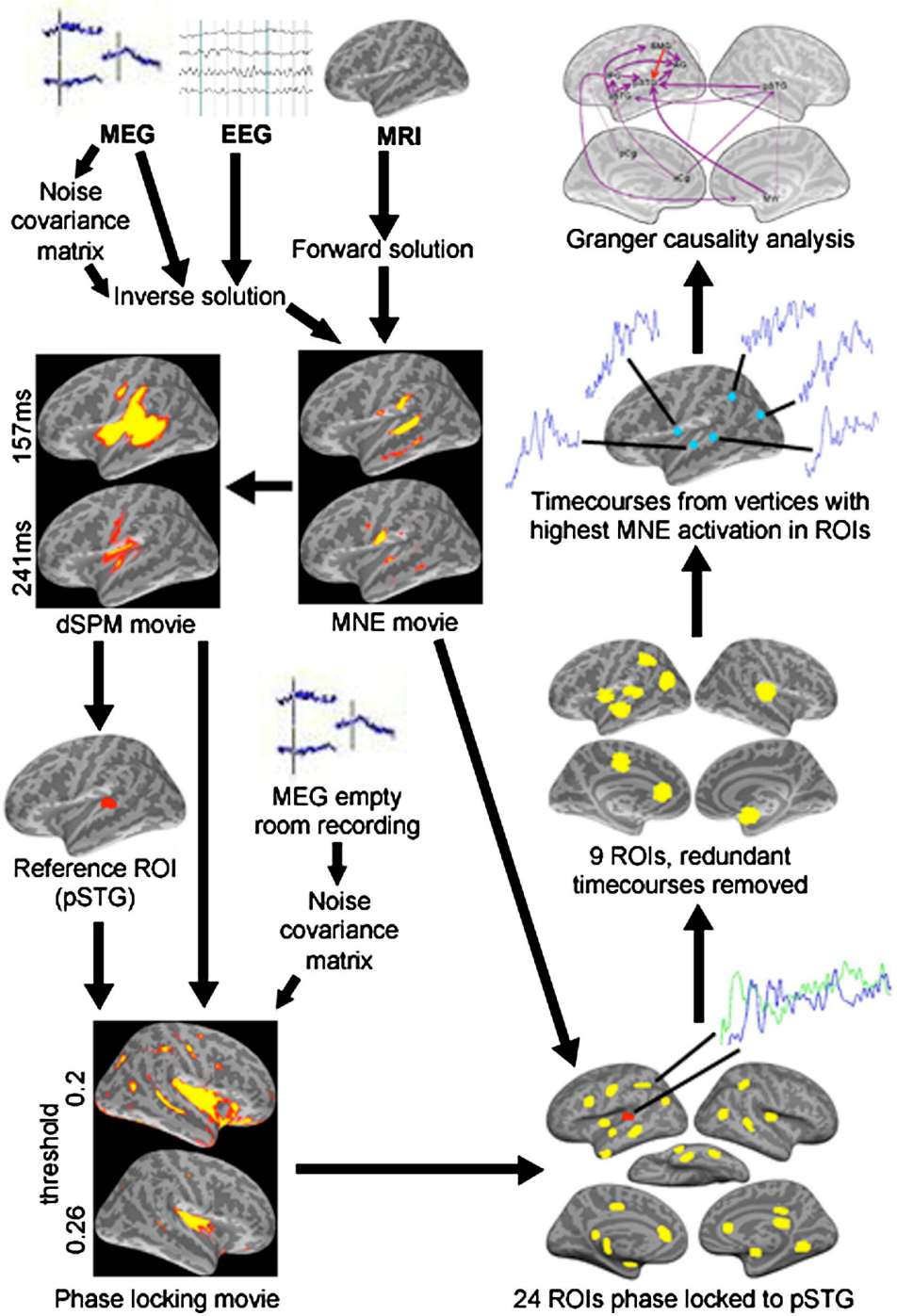
Contexts:

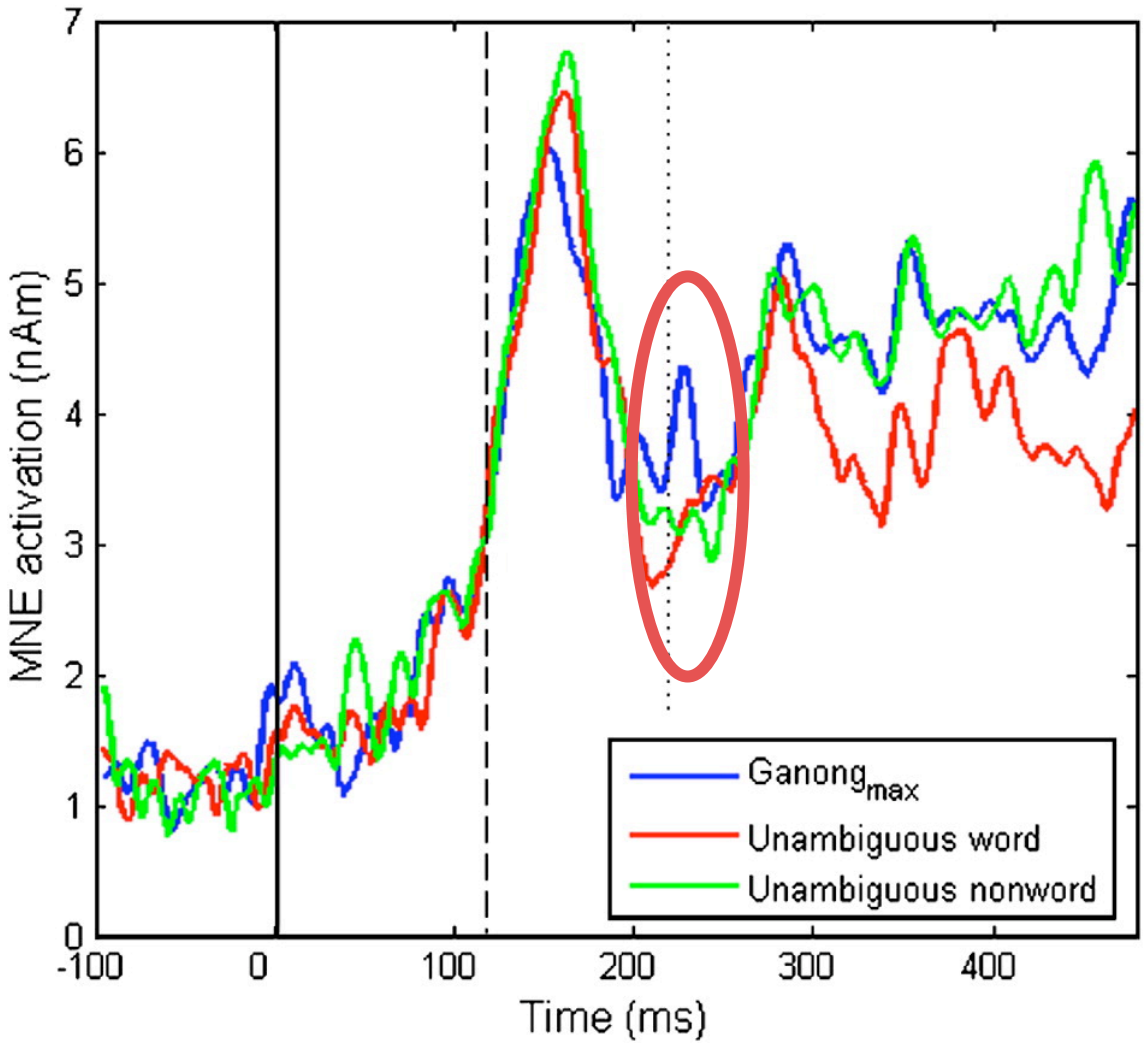
_ampoo

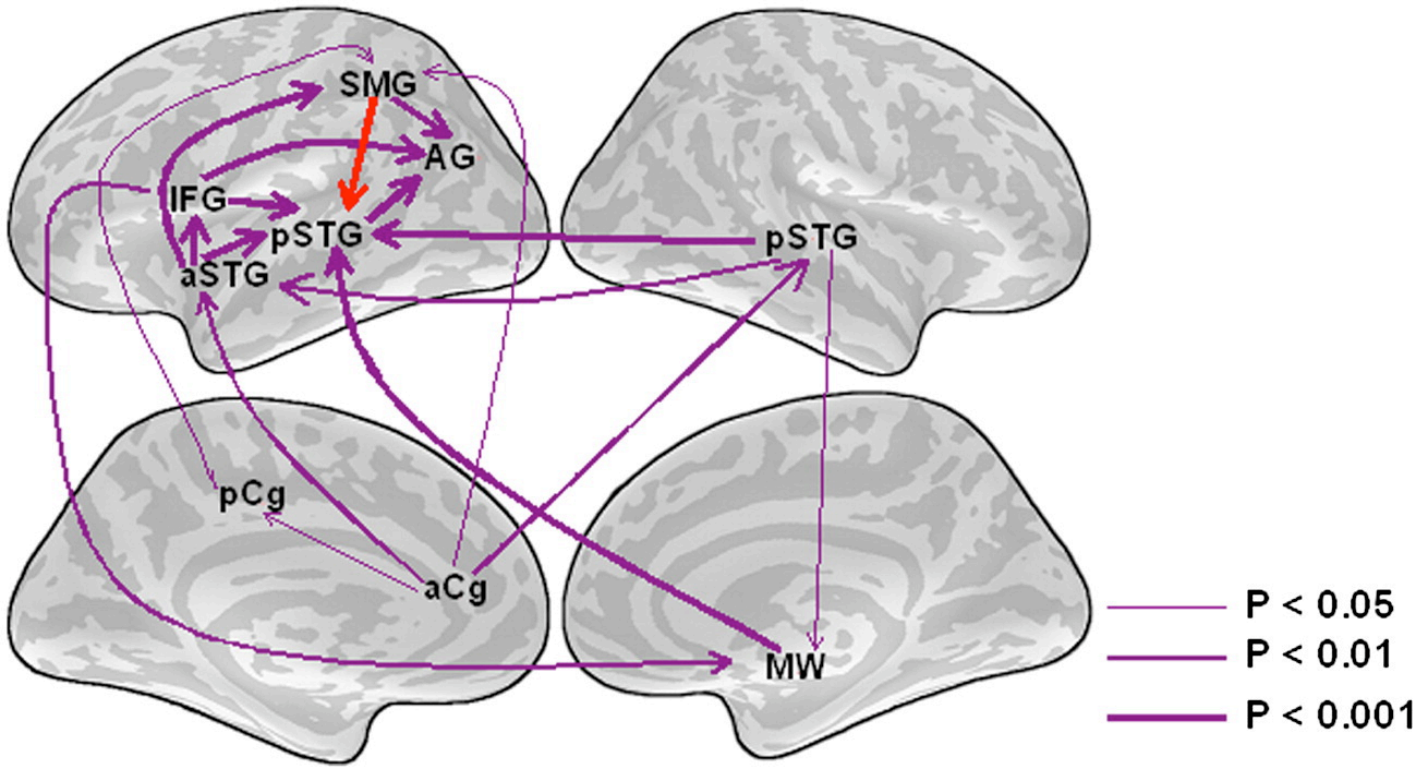
_andal

Behavioral Results




MEG
EEG
MRI
Noise covariance matrix
Inverse solution
Forward solution
157ms
241ms
dSPM movie
MNE movie
Granger causality analysis
Timecourses from vertices with highest MNE activation in ROIs
9 ROIs, redundant timecourses removed
Reference ROI (pSTG)
MEG empty room recording
Noise covariance matrix
threshold
0.2
0.26
Phase locking movie
24 ROIs phase locked to pSTG


MNE activation (nAm)
Time (ms)
Ganong$_{max}$
Unambiguous word
Unambiguous nonword
0
1
2
3
4
5
6
7
-100
0
100
200
300
400


SMG
AG
IFG
pSTG
aSTG
pSTG
pCg
aCg
MW
P < 0.05
P < 0.01
P < 0.001

Summary (1)

Neuroimaging has continued to provide new methods of examining the neural basis of language processes

The application of new analytic techniques permits examination of causal relations between areas over time

These approaches can be extended to longer time periods and may afford information about the multiple operations that occur during processes such as sentence comprehension

Other developments (e.g., dynamic receptor mapping) are likely to occur

Summary (2)

These techniques are not easy to use or interpret

They are not likely to the universally applicable
(e.g., to diagnosis of learning problems)