

Syntax and Prosody in the Human Brain

Angela D. Friederici



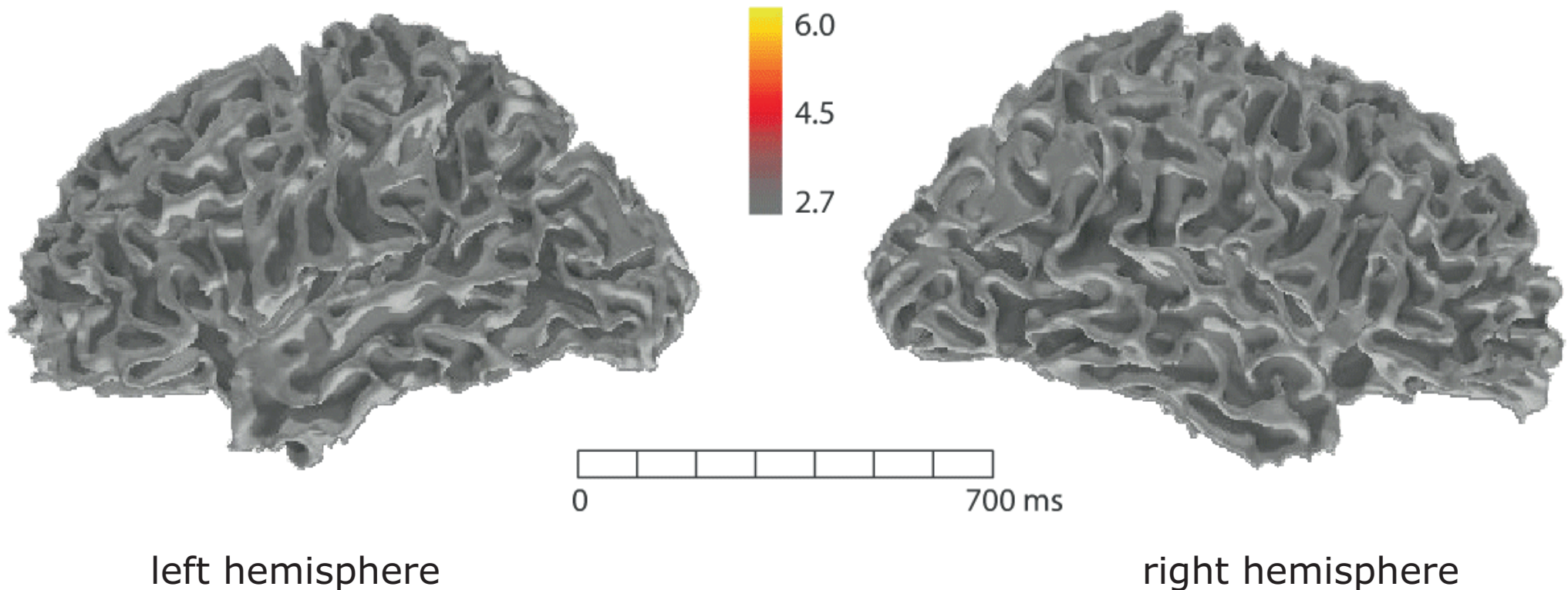
Max Planck Institute
for Human Cognitive and Brain Sciences
Leipzig, Germany

Language processing on-line

"Maria weiß, dass der Bauer beim Acker rastet."



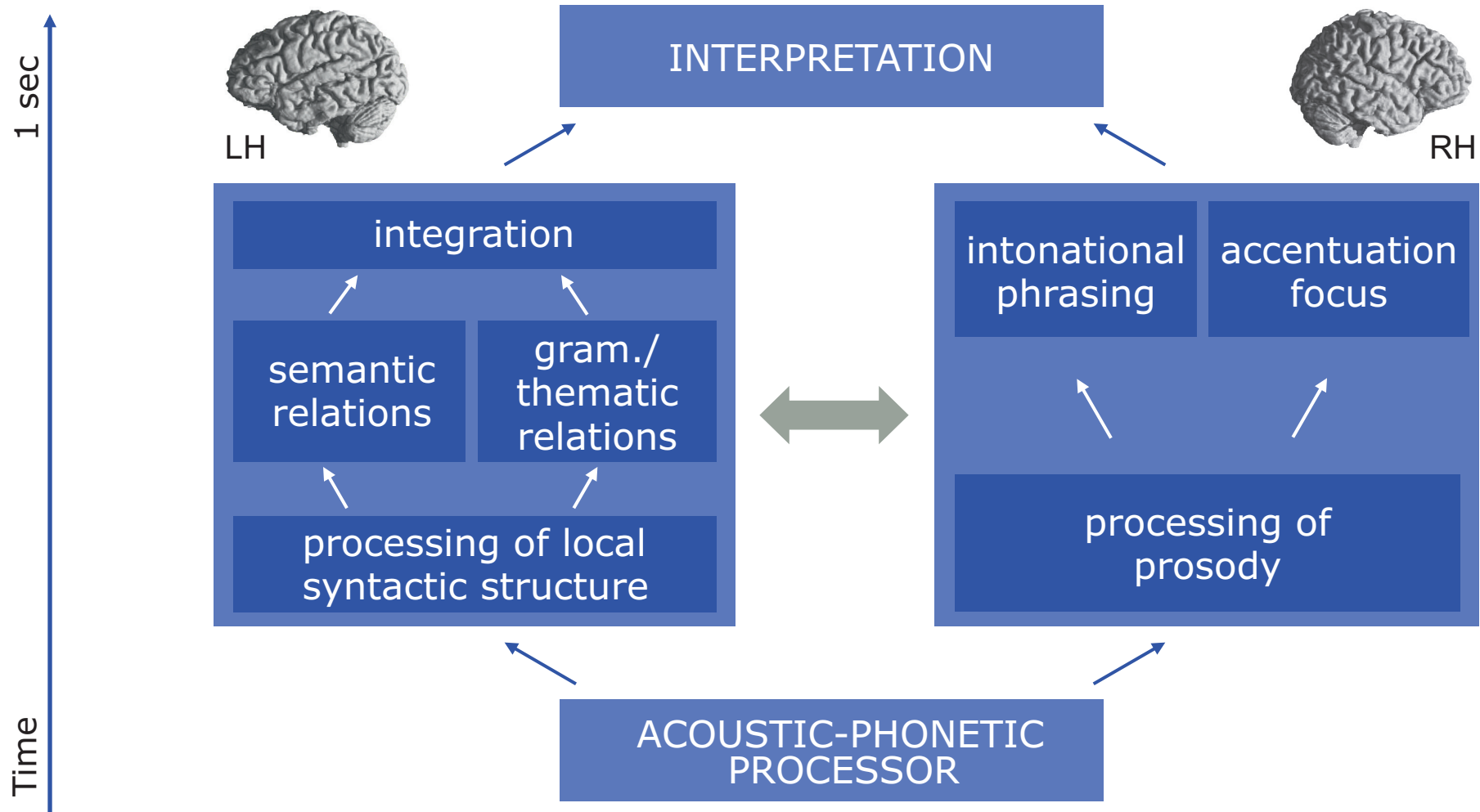
"Mary knows, that the farmer rests close to the field."



left hemisphere

right hemisphere

Model of auditory language processing



Source: Friederici & Alter, *Brain and Language*, 2004

Neuroscience of language

Which brain areas support language processing

- acoustic,
- prosodic,
- syntactic
- and semantic processes?

Neuroscience of language

Which brain areas support language processing

- acoustic,
- prosodic,
- syntactic
- and semantic processes?

Teasing the brain

There are in principle three possibilities to investigate specific subprocesses:

1. Introduction of violation of a specific information type (e.g. syntax and prosodic violation)
2. Variation of the amount of a specific information type (e.g. syntactic complexity)
3. Systematic variation of the presence/absence of a specific information type (e.g. syntax, prosody)

Stimuli: Violation of information type

correct

Das Baby wurde gefüttert.
The baby was fed.



semantically incorrect

Das Lineal wurde gefüttert.
The ruler was fed.



syntactically incorrect

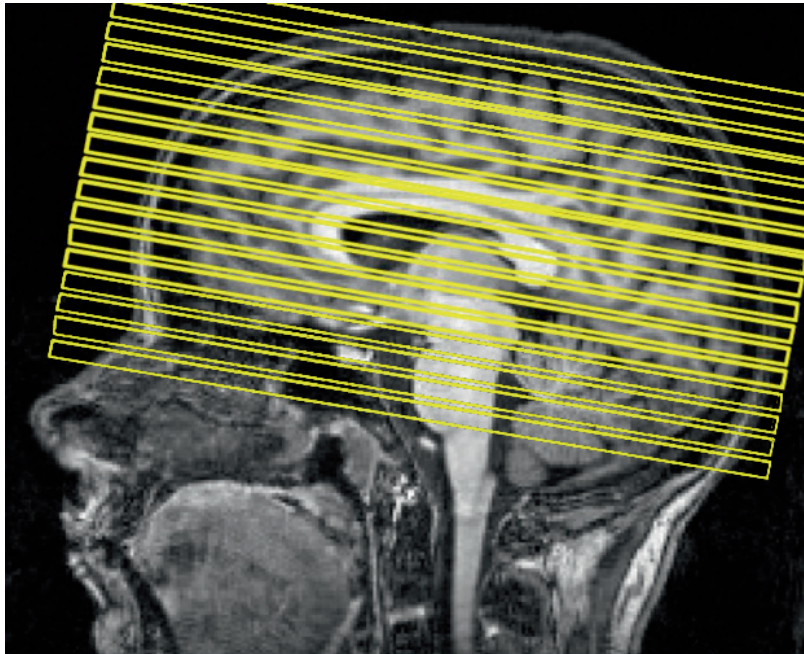
Die Gans wurde im gefüttert.
The goose was in the fed.



filler item correct

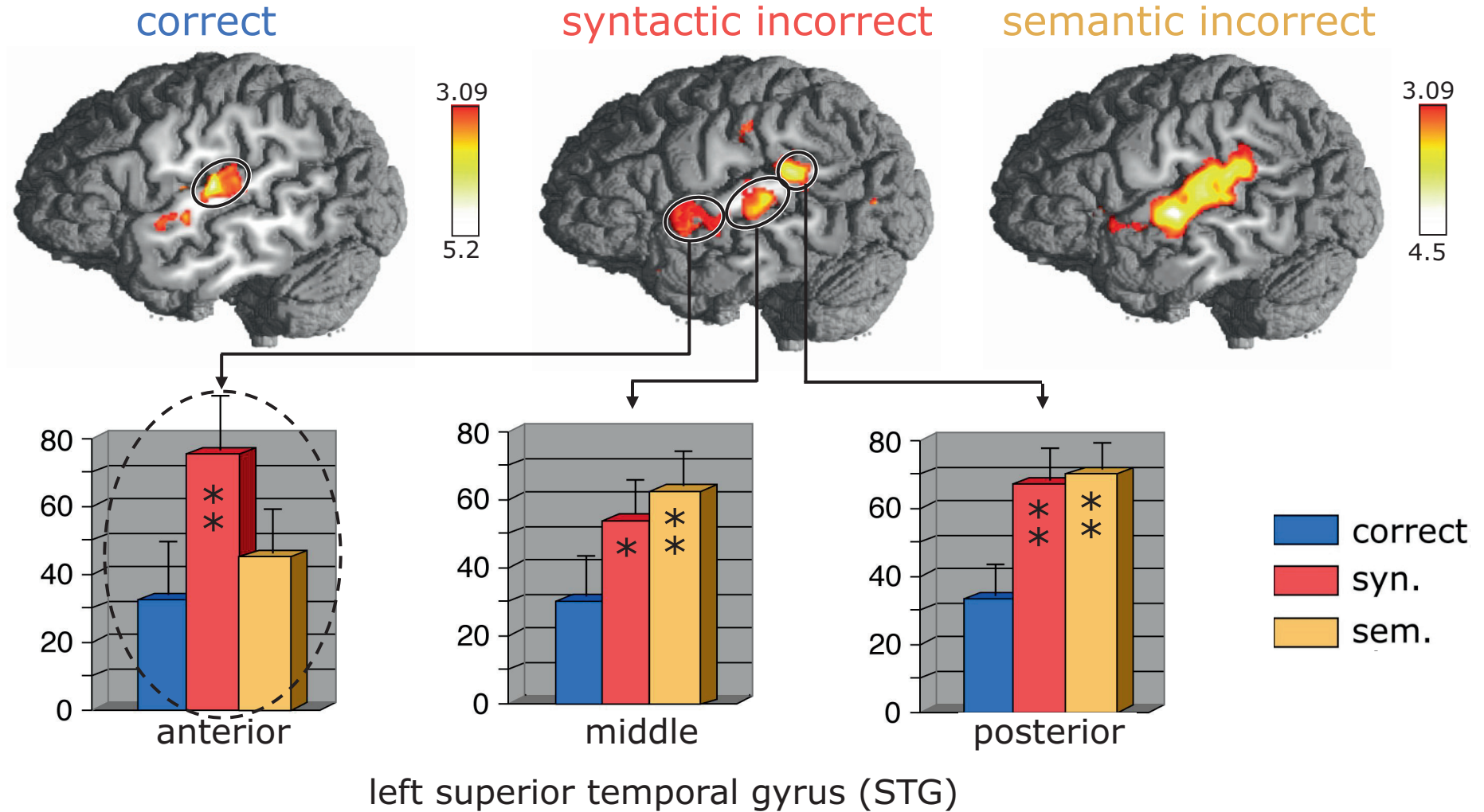
Die Kuh wurde im Stall gefüttert.
The cow was in the barn fed.

fMRI method



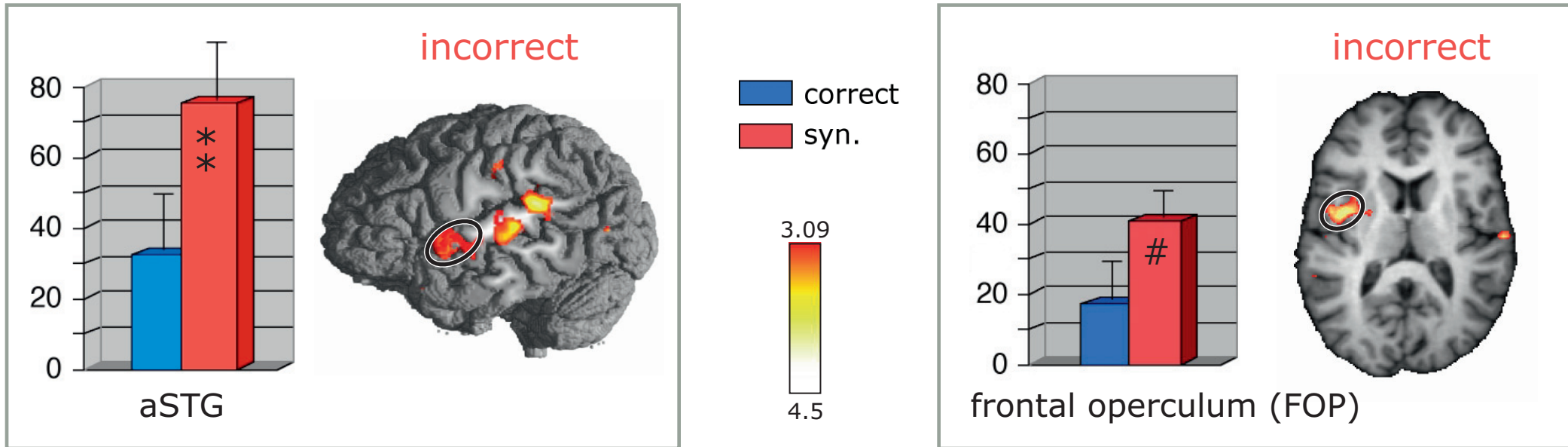
- **MRT:** 3 T Bruker Medspec 30/100 / 3 T Siemens Trio
Anatom. contrasts: T_1 -weighted 3D MDEFT sequence (128 sagittal slices)
Functional contrasts: T_2^* -weighted EPI sequence; TR = 2 s; TE = 40 ms
- **Slices:** horizontal slices parallel to the AC-PC line covering the perisylvian cortex; thickness = 4 mm; skip = 2 mm; 3 mm² *in-plane* and 7 mm *through-plane* resolution.

fMRI evidence



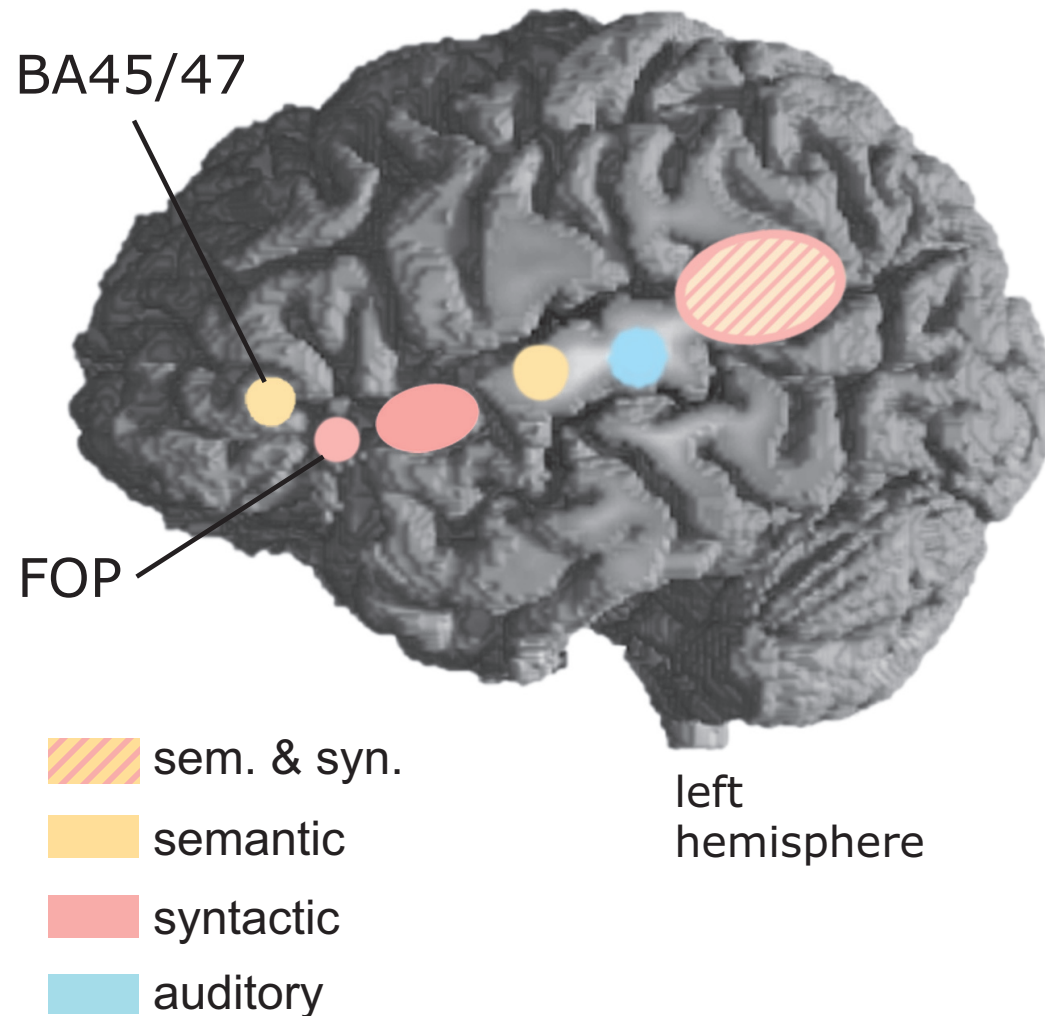
Source: Friederici, Rüschemeyer, Hahne & Fiebach, *Cerebral Cortex*, 2002

Syntactic processes: Violation



- aSTG > : Specific for syntactic violation
- FOP > : Specific for syntactic violation
- pSTG: Less specific for semantic & syntactic violation

Neurotopography of syntactic and semantic processes



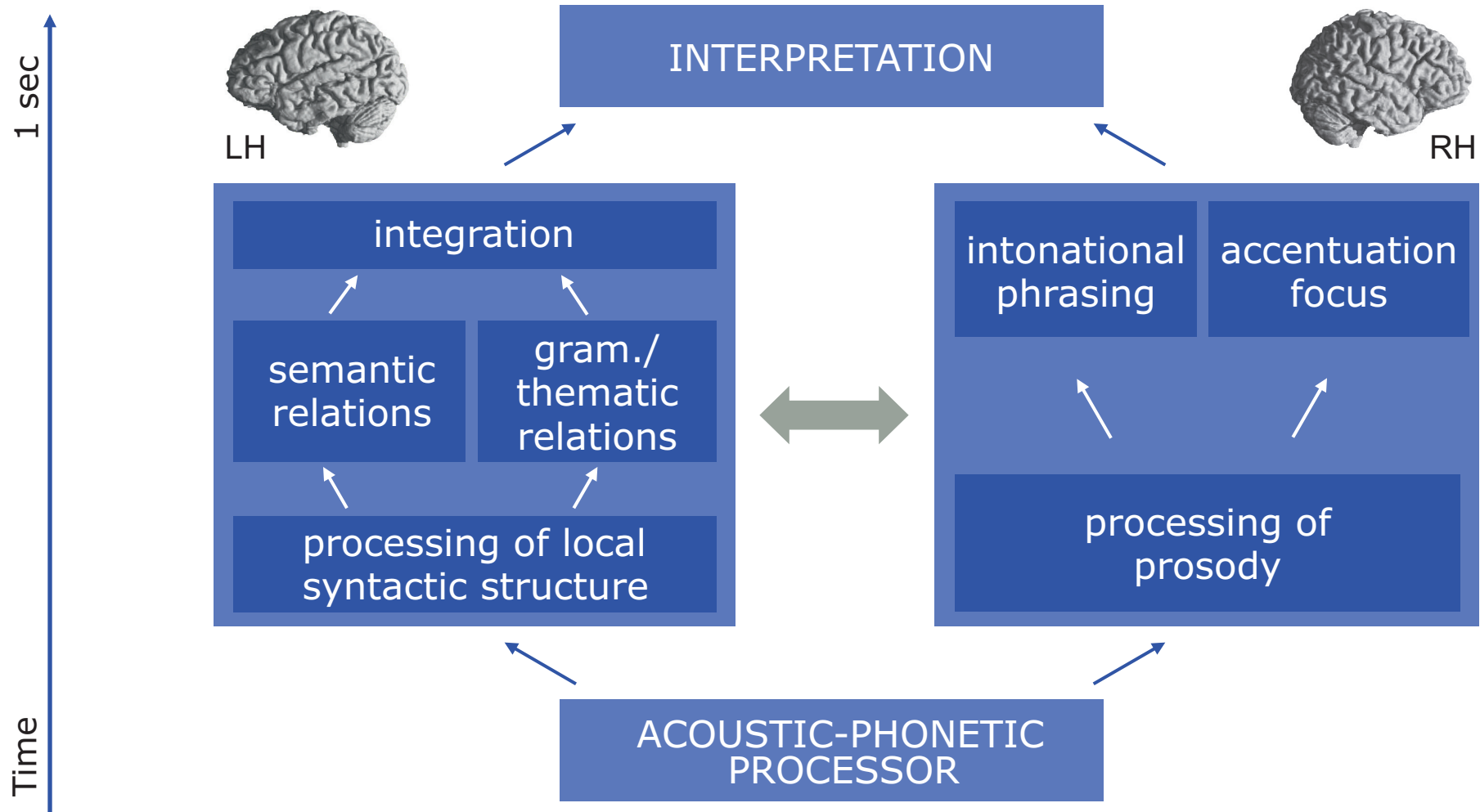
Semantic processes

- middle and posterior portion of the left superior temporal gyrus
- BA45/47 in the left inferior frontal gyrus

Syntactic processes

- anterior portion of the left superior temporal gyrus
- frontal operculum (FOP) in the left inferior frontal gyrus

Model of auditory language processing



Source: Friederici & Alter, *Brain and Language*, 2004

Which brain areas support early structure building process?

Hypothesis:

- early process:
- frontal operculum in the IFG*
 - anterior portion of the STG*
- late process:
- posterior portion of the STG

* were used as priors for MEG localization

MEG evidence

Stimuli

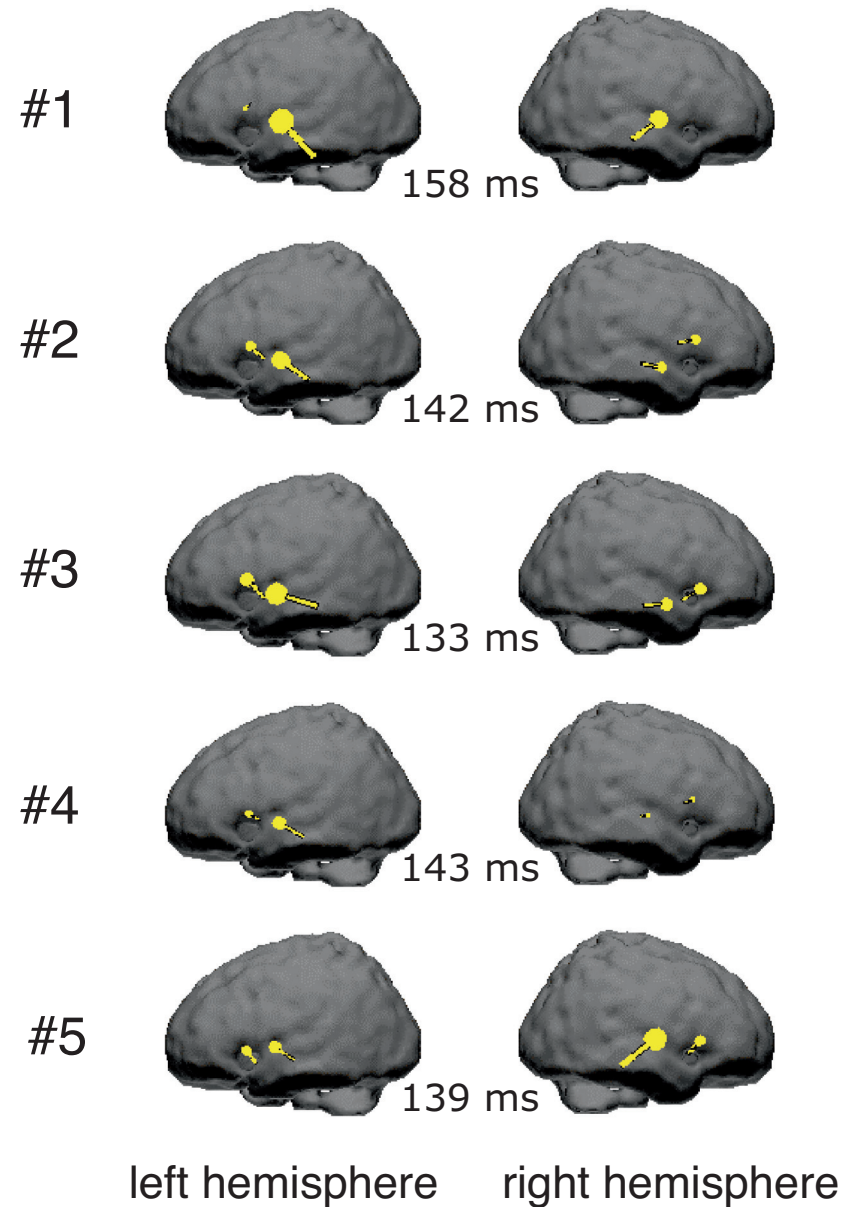
correct

Das Baby wurde gefüttert.
The baby was fed.

syntactically incorrect

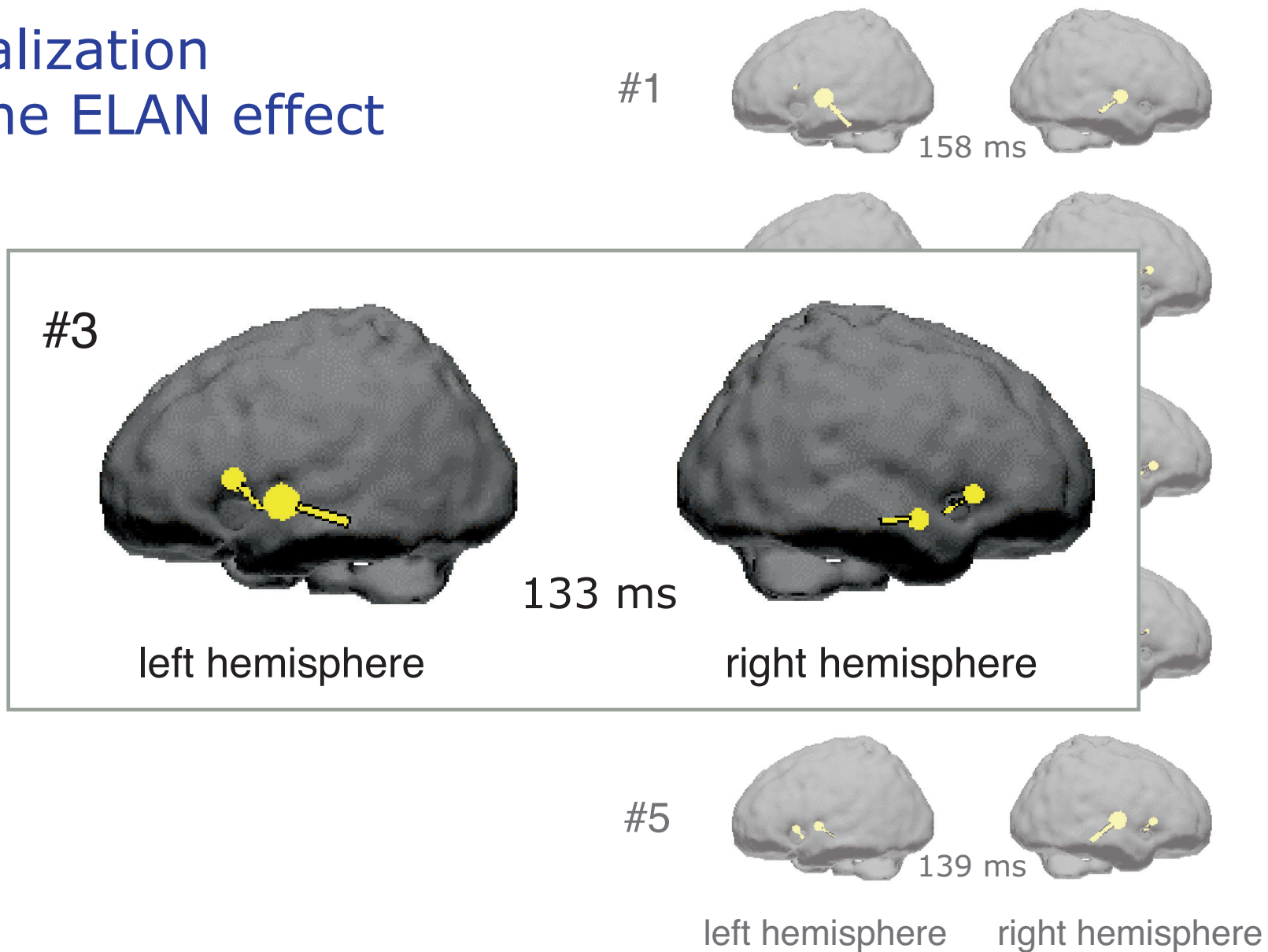
Die Gans wurde im gefüttert.
The goose was in the fed.

Localization of the ELAN effect



Source: Friederici et al., *Human Brain Mapping*, 2000

Localization of the ELAN effect



Source: Friederici et al., *Human Brain Mapping*, 2000

Conclusion

The early left anterior negativity (ELAN) is generated in the anterior temporal and in the inferior frontal cortex.

Is the ELAN a syntax effect (syntactic incorrectness) or due to prosodic incongruency?

ELAN: Syntax vs Prosody

Syntax (phrase structure violation) & prosody (change in F0)

Sentence, e.g.:

Syntax

Prosody

■ Die Küche wurde geputzt.
The kitchen was cleaned.

+

+

■ Das Fenster wurde im geputzt.
The window was in-the cleaned.

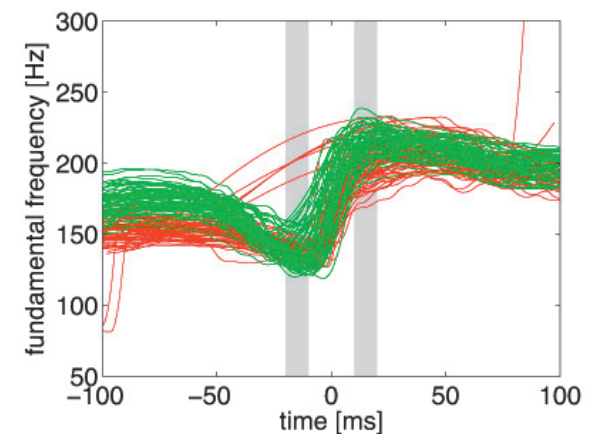
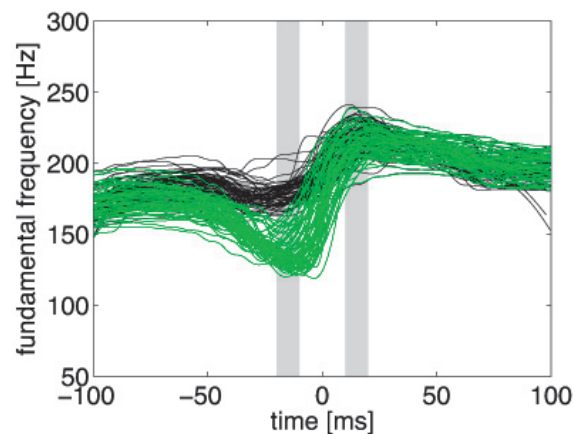
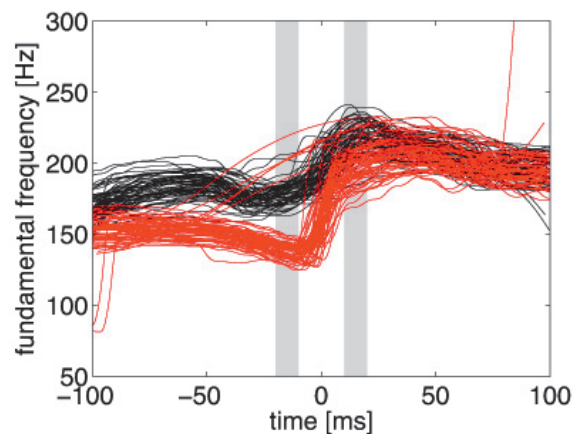
-

~

■ Der Boden wurde X geputzt.
The floor was X cleaned.

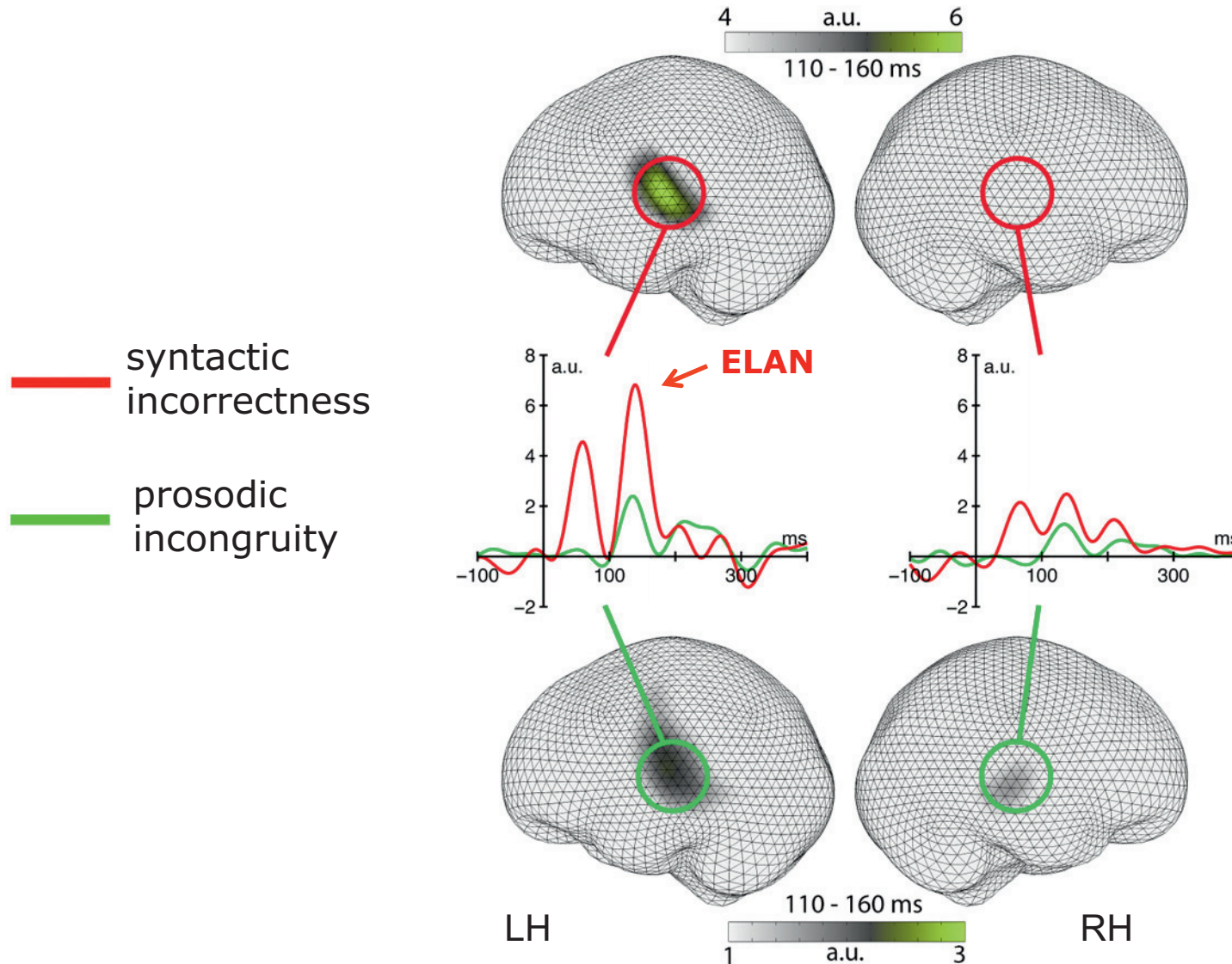
+

~



Source: Herrmann, Maess, Hahne, Schröger & Friederici, *NeuroImage*, 2011

MEG experiment



Source: Herrmann, Maess, Friederici, *Neuroscience Letters*, 2011

Conclusion

ELAN is not due to prosodic incongruity, but to syntactic incorrectness.

Discussion in the literature: ELAN

Visual experiment by Dikker et al. (2009)

correct: The discovery was reported

incorrect: The discovery was in the reported

Visual presentation → ELAN located in the visual cortex

More general claim → ELAN is generated in the sensory cortex

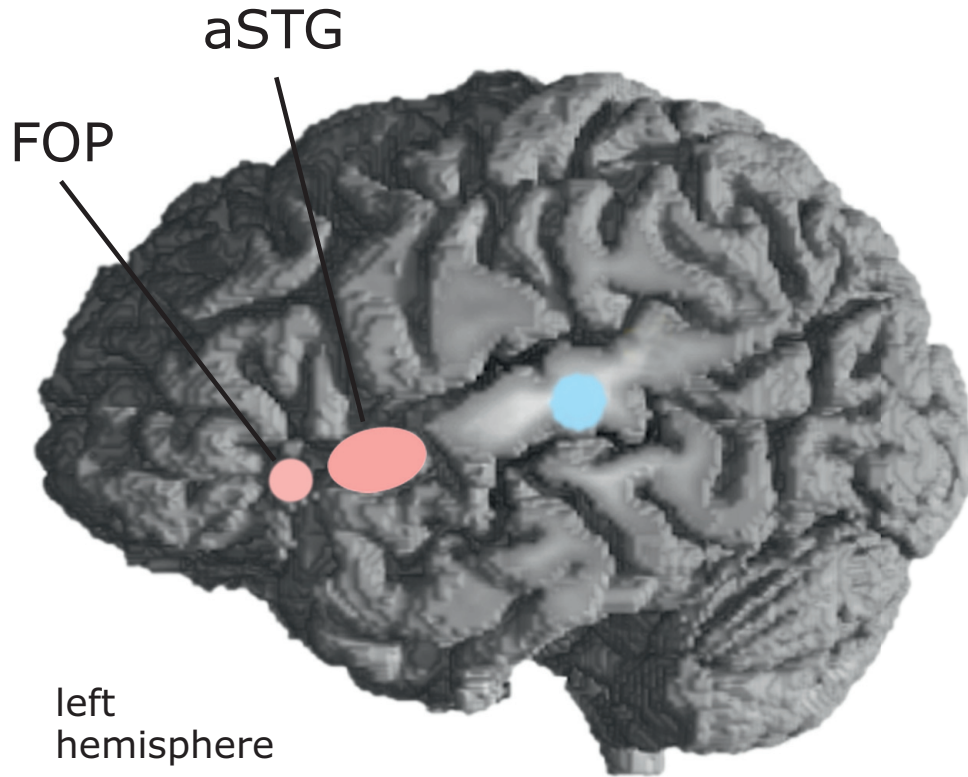
Is the ELAN located in the auditory cortex?

ELAN and the auditory cortex

2 × 2 design (phrase structure violation × spatial location (interaural time difference by 0.2 ms))

Sentence, e.g.:	Syntax Congruity	Spatial Lateralization
■ Das Obst wurde geerntet. <i>The fruit was harvested.</i>	correct +	standard +
■ Die Gerste wurde im geerntet. <i>The barley was in-the harvested.</i>	incorrect -	standard +
■ Das Obst wurde geerntet. <i>The fruit was harvested.</i>	correct +	deviant -
■ Die Gerste wurde im geerntet. <i>The barley was in-the harvested.</i>	incorrect -	deviant -

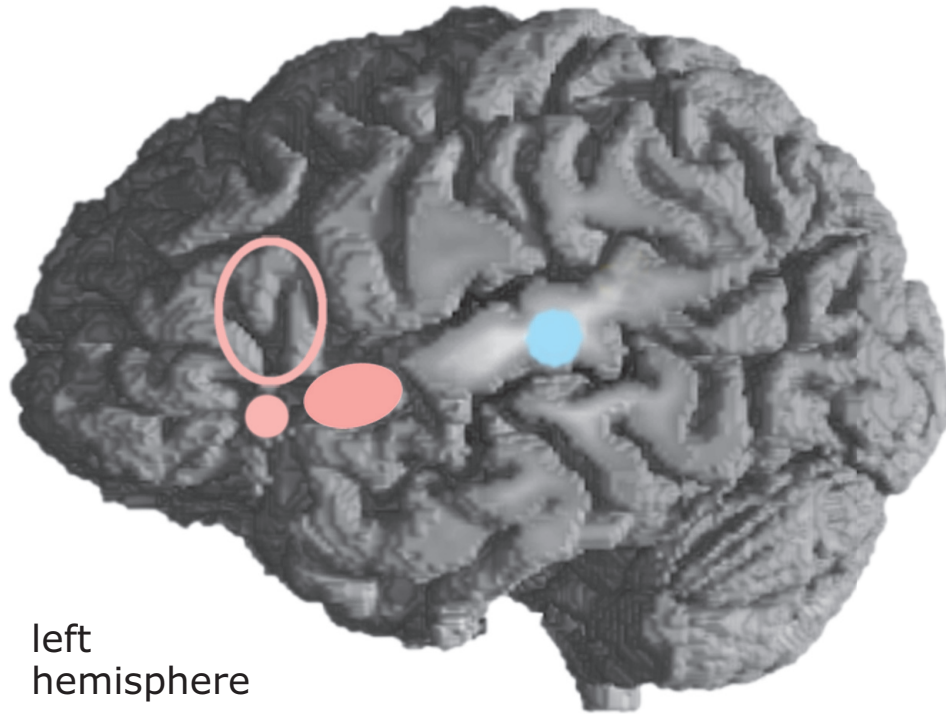
Syntactic violation



- local syntax
- auditory

ELAN is not located in the auditory cortex, but in the left aSTG and the FOP.

Neuroanatomy of syntactic processes



local syntax

Broca's area

What is the function of Broca's area?

The function of Broca's area: Patient evidence

Studies with patients suffering from lesions in Broca's area have syntactic deficits:

- a) They produce agrammatic sentences.
- b) They have problems in comprehending syntactically complex sentences.

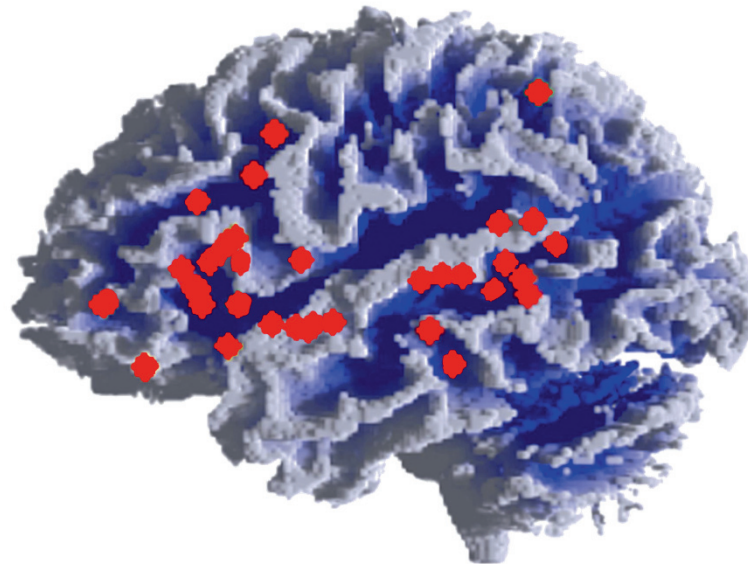
Hypothesis:

Syntax is located in Broca's area.

(see also Grodzinsky, 2000)

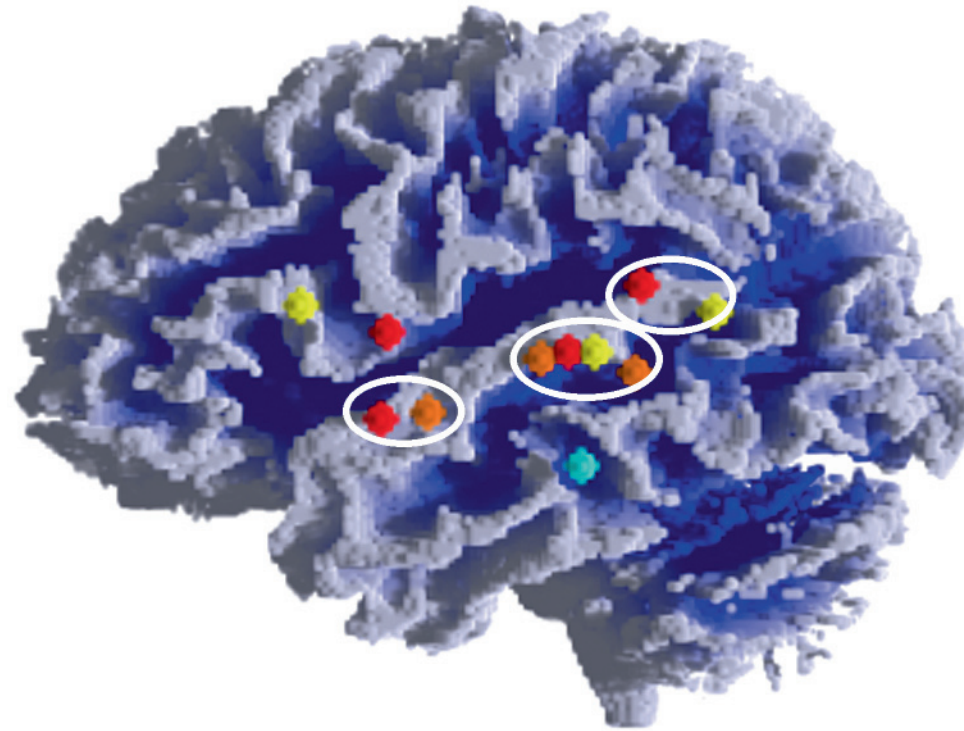
The function of Broca's area: fMRI evidence

A metaanalysis of 15 studies on syntactic processing was conducted.



Metaanalysis A

Syntactic violations: Ungrammatical > grammatical



 Kuperberg et al. 2000

 Meyer et al. 2000

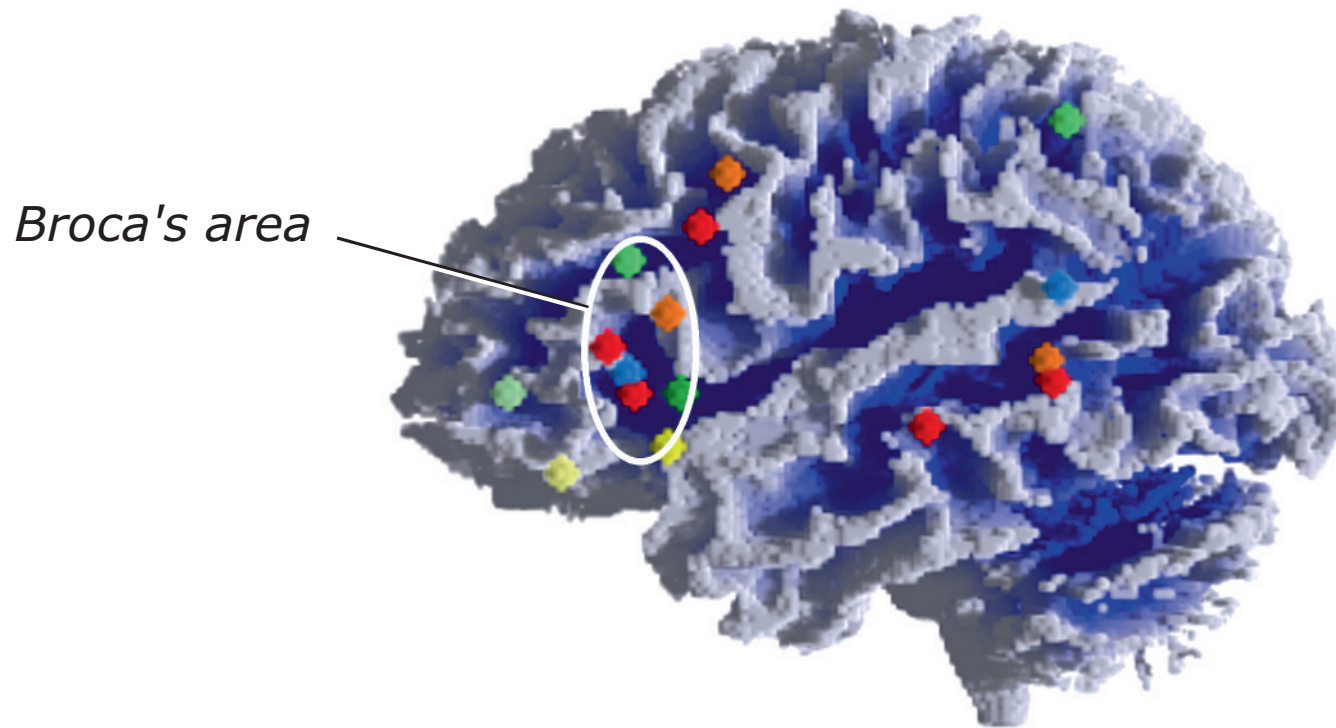
 Embick et al. 2000



 Friederici et al. 2003

Source: Friederici, 2004. In: Gazzaniga (ed.), *The Cognitive Neurosciences III*

Metaanalysis B

Syntactic complexity/working memory high > low



- | | | | |
|---|--|---|--------------------------|
|  | Stromswold et al. 1996, Caplan et al. 1998/1999/2000 |  | Roeder et al. 2002 |
|  | Cooke et al. 2001 |  | Ben-Schachar et al. 2003 |
|  | Fiebach et al. 2001 | | |

Source: Friederici, 2004. In: Gazzaniga (ed.), *The Cognitive Neurosciences III*

Parametric manipulation of syntactic complexity I: Non-canonical sentences

canonical (S-IO-DO)

Heute hat der Opa dem Jungen den Lutscher geschenkt.

Today has the grandfather(nominative) the boy (dative) the lollipop(accusative) given (as a present).

medium complexity (IO-S-DO)

Heute hat dem Jungen der Opa ___ den Lutscher geschenkt.

Today has the boy the grandfather the lollipop given.

high complexity (IO-DO-S)

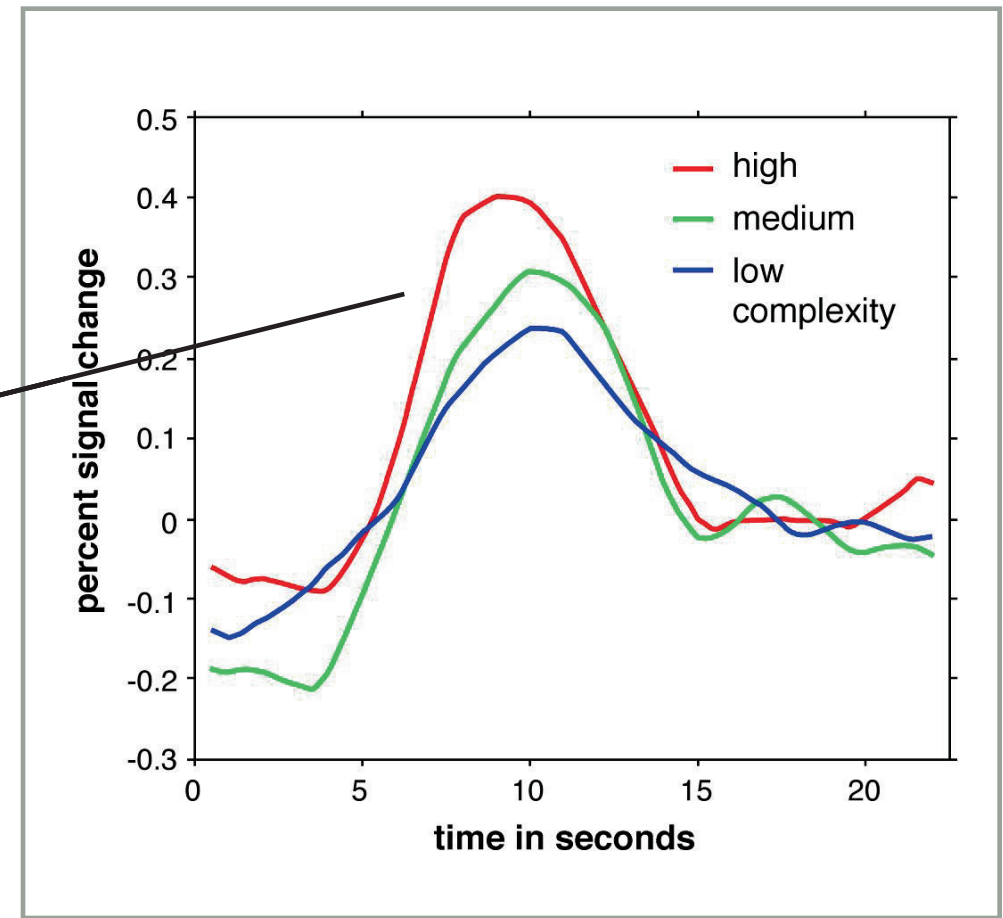
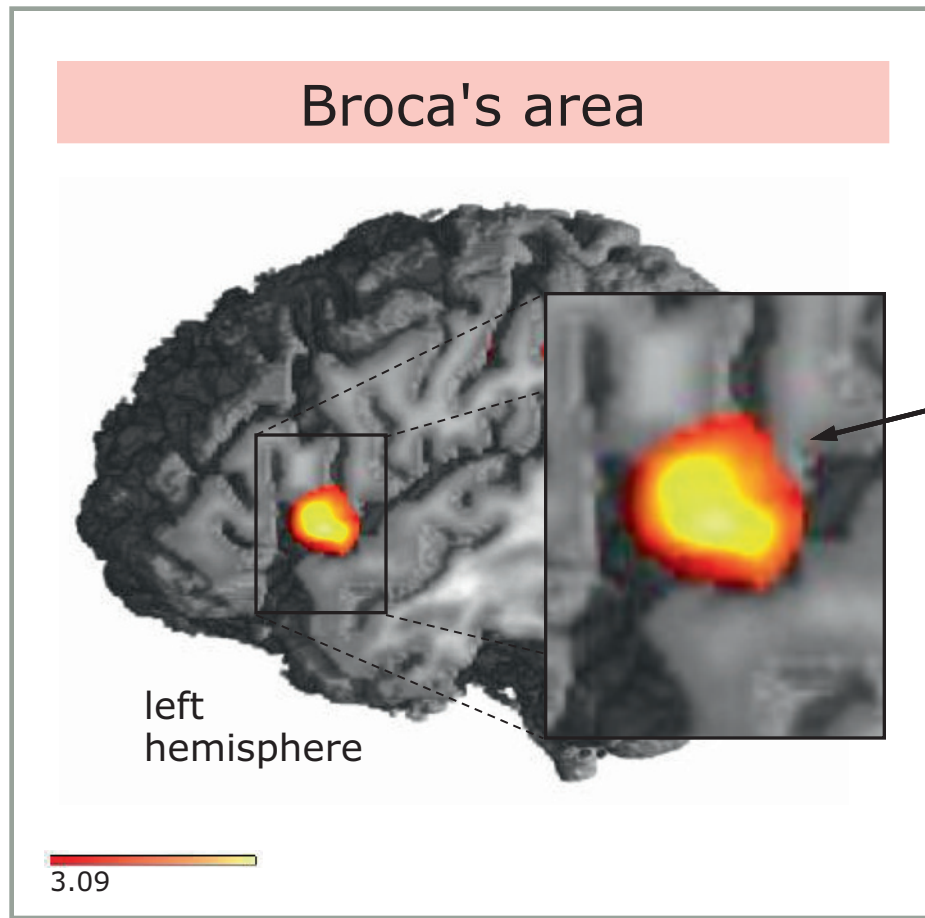
Heute hat dem Jungen den Lutscher der Opa ___ ___ geschenkt.

Today has the boy the lollipop the grandfather given.

S = subject noun phrase, IO = indirect object argument, DO = direct object

Result of ROI analysis

Broca's area & syntactic complexity



**Syntactically complex sentences are processed
in Broca's area (BA 44).**

What is the contribution of working memory when
processing syntactic complex sentences?

2 x 2 Design with the factors working memory (WM) and syntactic hierarchy (SH)

Distance of Dependency (WM)

Long (8)

Short(4)

Type of Structure (SH)

Sentence Structure

Sentence Structure

Embedded



Non Embedded



Examples of stimuli items

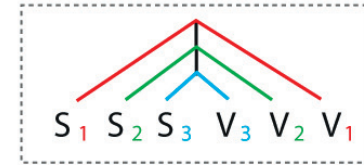
Peter wusste, dass ...

Peter knew that ...

— hierarchy & long distance —

[**Maria**, [**die** Hans, [**der** gut **aussah**], **liebte**], Johann **geküsst hatte**.]

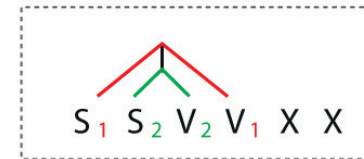
Maria who loved Hans who was good looking kissed Johann.



— hierarchy & short distance —

[**Maria**, [**die weinte**], Johann **geküsst hatte**] und zwar gestern abend.]

Maria who cried kissed Johann and that was yesterday night.



— linear & long distance —

[**Achim** den großen Mann gestern am späten Abend **gesehen hatte**.]

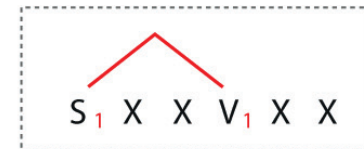
Achim saw the tall man yesterday late at night.



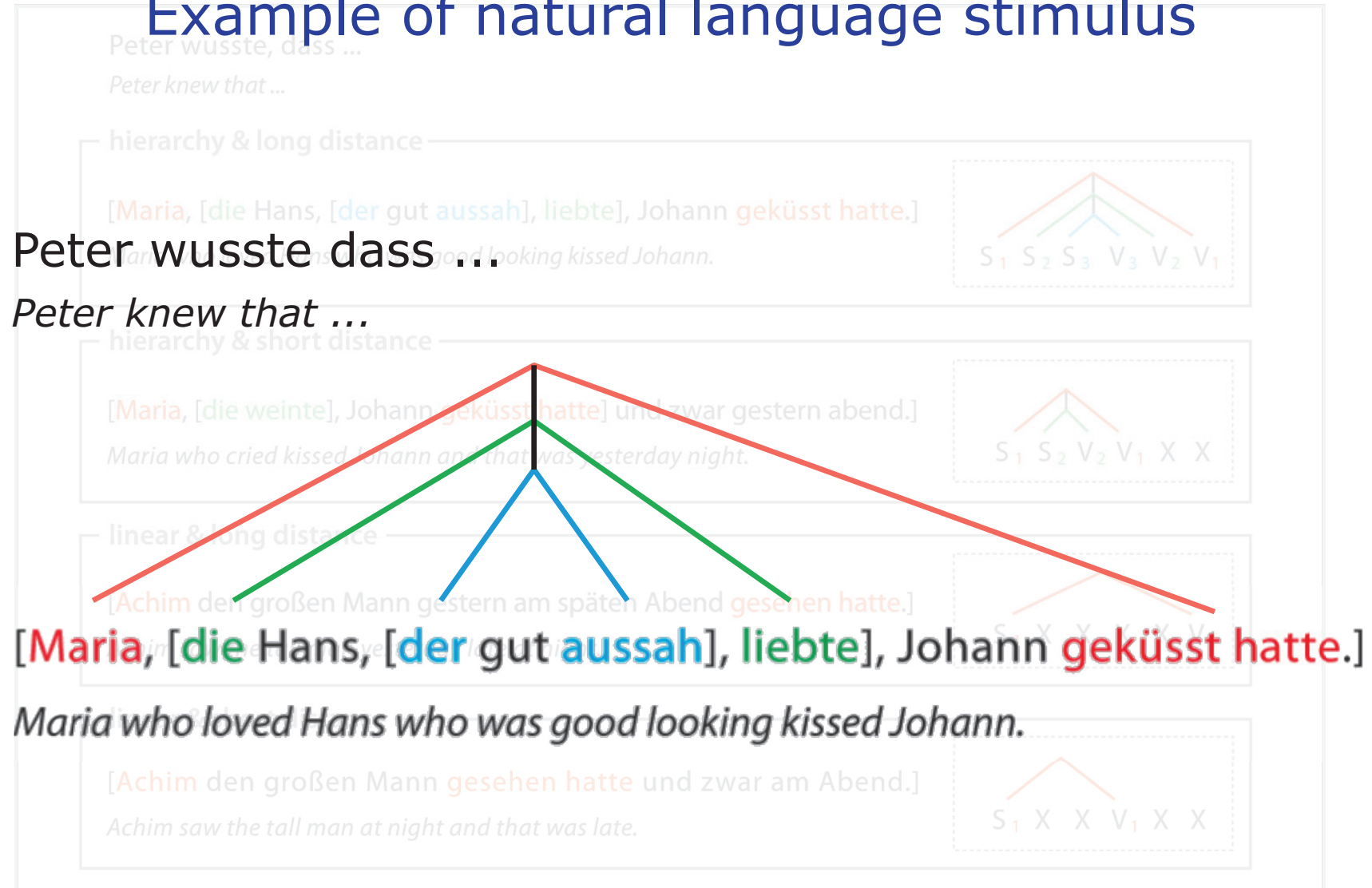
— linear & short distance —

[**Achim** den großen Mann **gesehen hatte** und zwar am Abend.]

Achim saw the tall man at night and that was late.

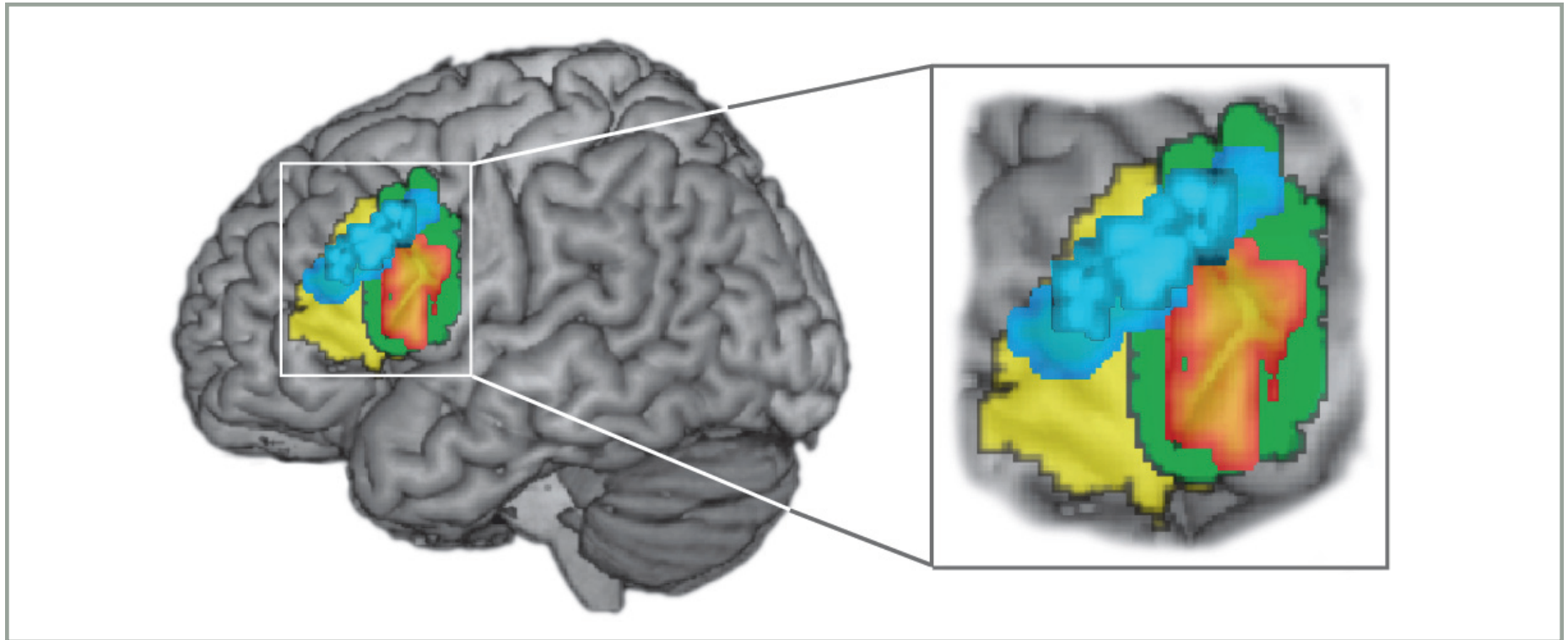


Syntactic hierarchy: Example of natural language stimulus



Source: Makuuchi, Bahlmann, Anwander & Friederici, PNAS, 2009

Activation in IFG: ROI analysis Broca's area



Orange: main effect of syntactic hierarchy

Light Blue: main effect of distance (WM)

Green: BA 44

Yellow: BA 45

Source: Makuuchi, Bahlmann, Anwander & Friederici, PNAS, 2009

Conclusion: Syntax and WM in left IFG

Syntactic hierarchy can be segregated from working memory.

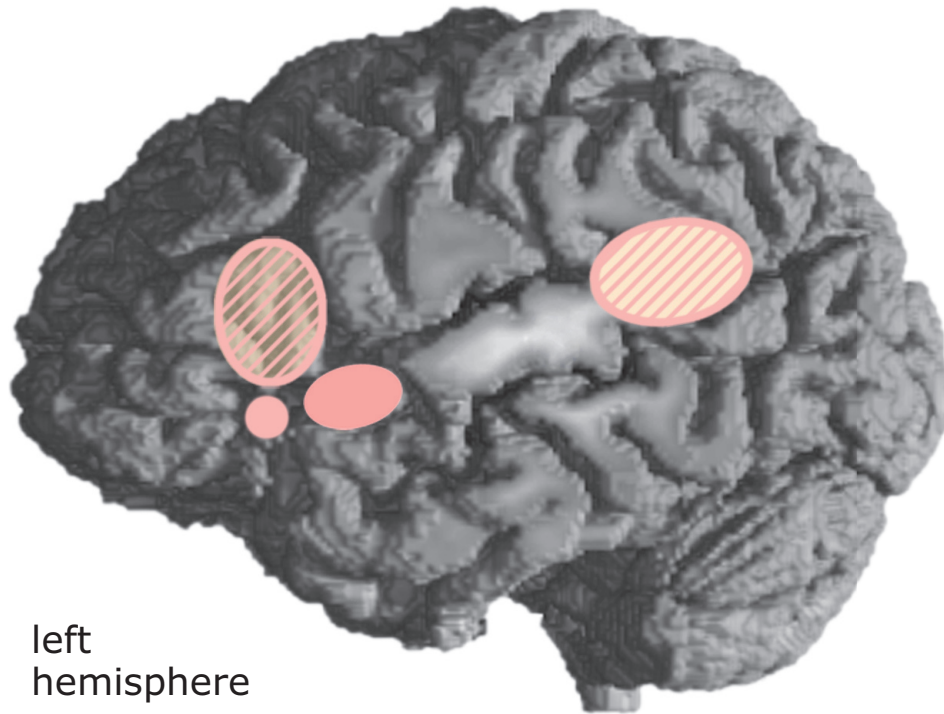
Syntactic hierarchy

→ BA 44, left pars opercularis

Distance (WM)

→ left inferior frontal sulcus

The neural basis of syntax



Local phrase structure

- frontal operculum
- anterior STG

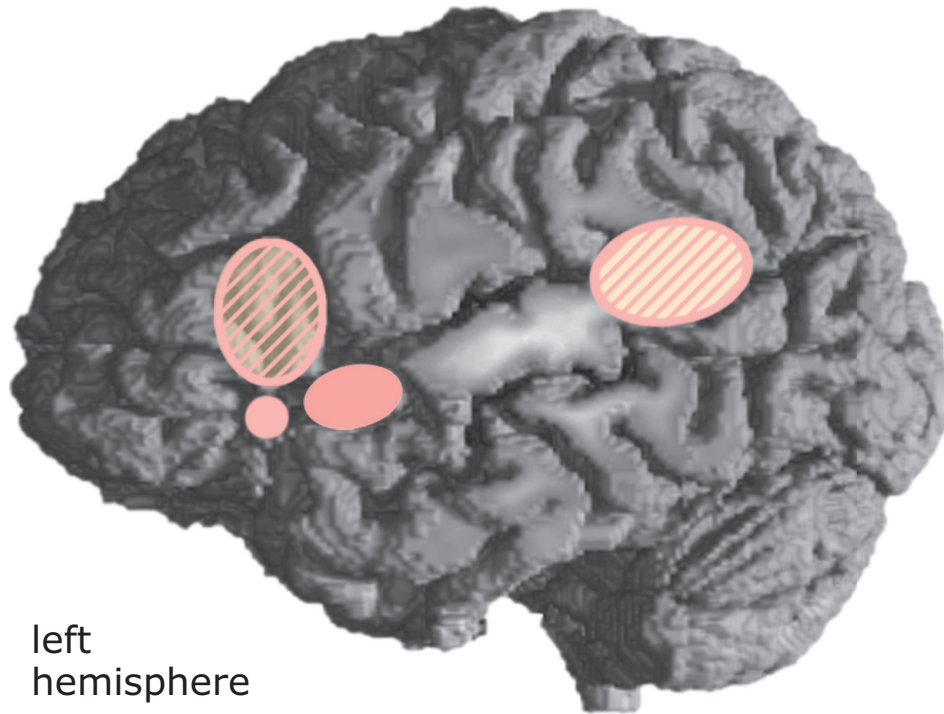
Complex hierarchical structure




- Broca's area
- posterior STG/STS ?

 hierarchical structures

 local structures

Function of posterior STG?



-  integration
-  hierarchical structures
-  local structures

Hypothesis:

post STG supports integration of semantic and syntactic information during processing of syntactic complex sentences

Syntactic complexity I: Non-canonical sentences

Gestern wurde erzählt, ...
Yesterday was told...

canonical (SOV), case marked

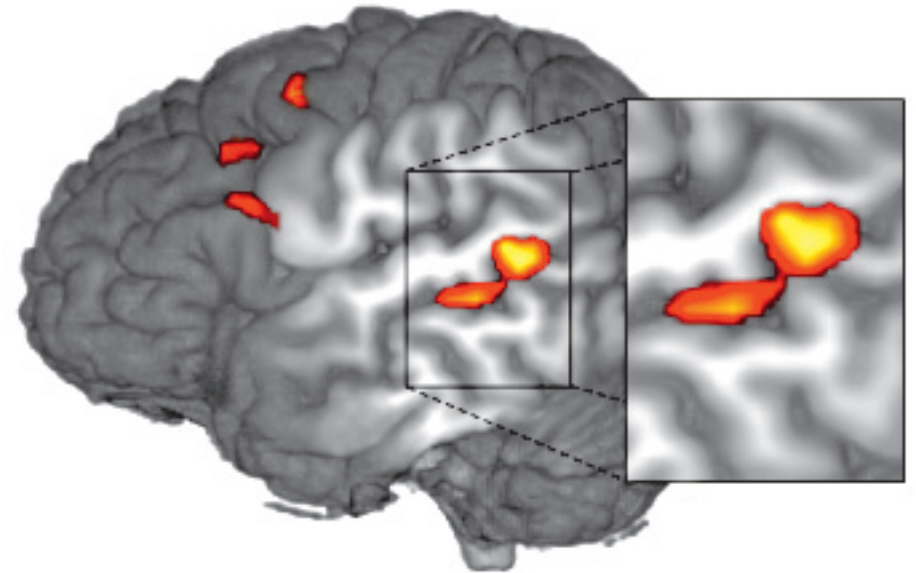
SO ...dass | der Junge | dem Lehrer | hilft.
...that [the boy]_{NOM} [the teacher]_{DAT} helps

non-canonical (OSV), case marked

OS ...dass | dem Jungen | der Lehrer | hilft.
...that [the boy]_{DAT} [the teacher]_{NOM} helps

Posterior STG/STS

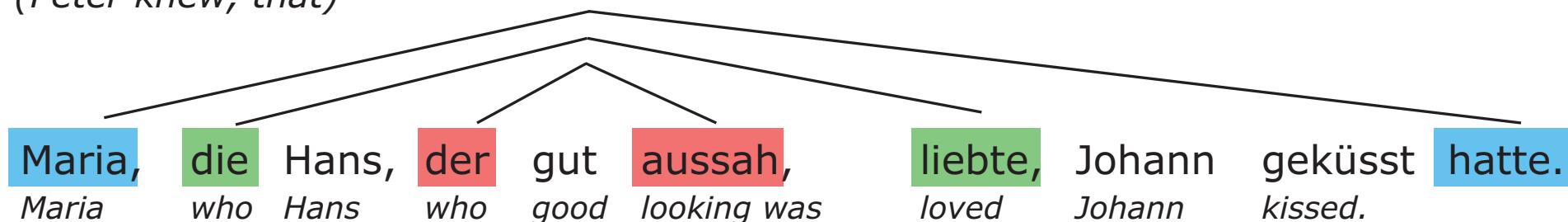
Object-first sentences



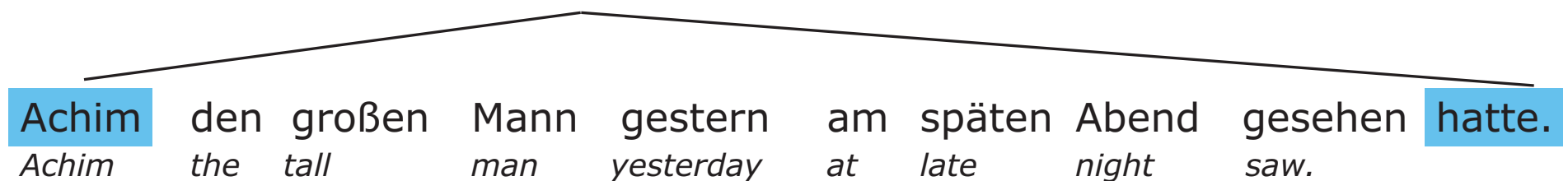
Source: Bornkessel et al., NeuroImage, 2005

Syntactic complexity II: Embedded sentences

Peter wusste, dass
(Peter knew, that)



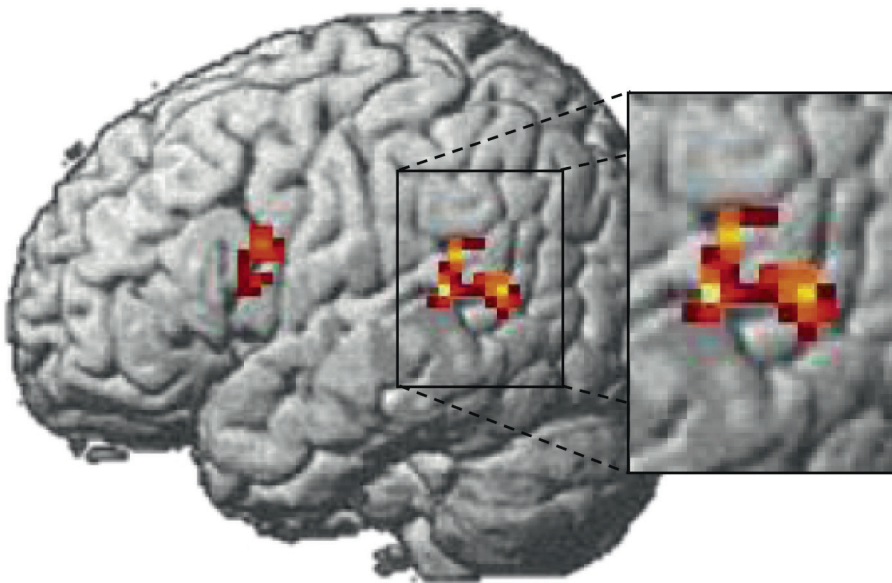
(Maria who loved Hans who was good looking kissed Johann)



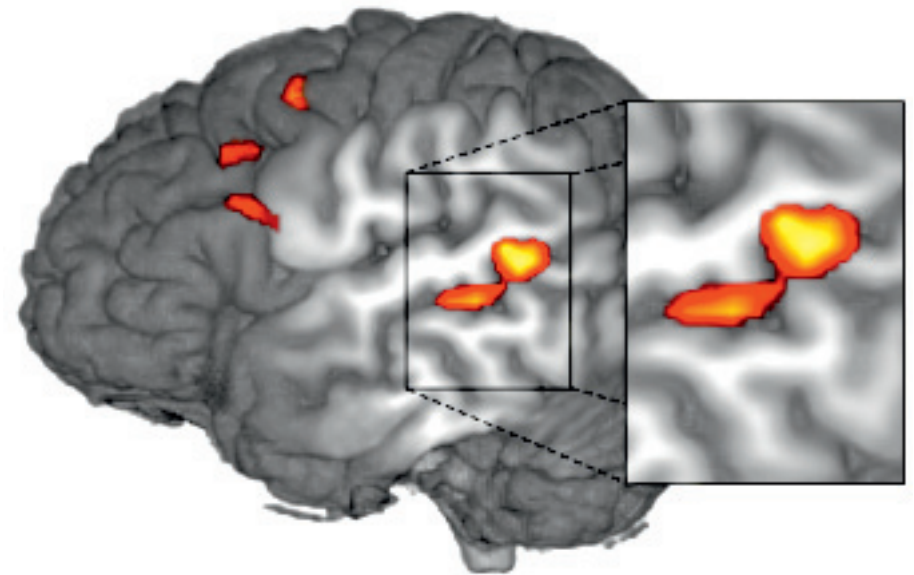
(Achim saw the tall man yesterday late at night)

Posterior STG/STS

Embedded sentences



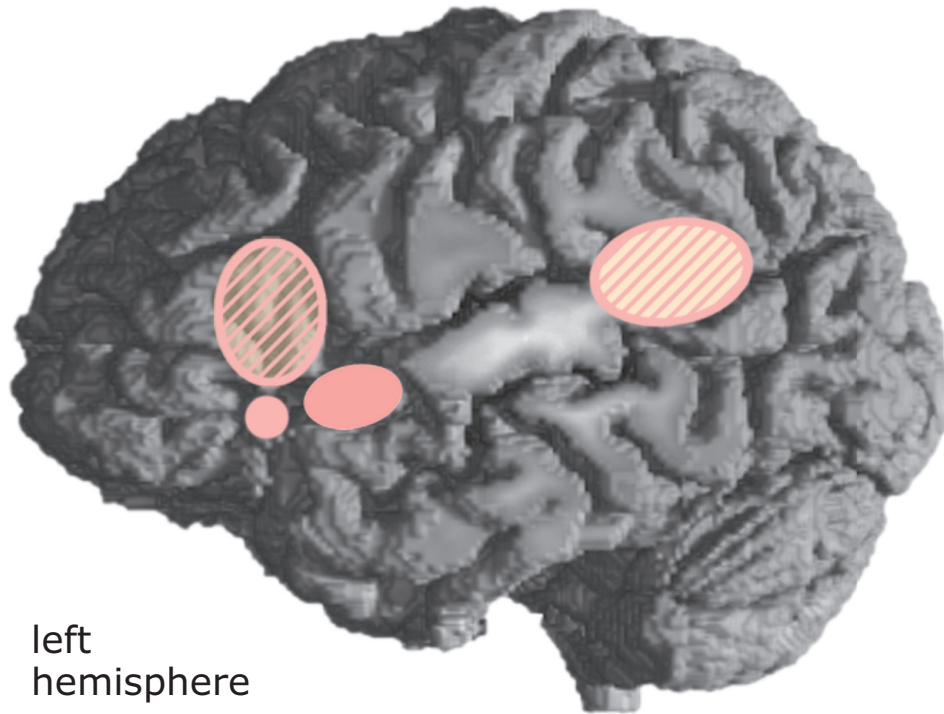
Object-first sentences



Source: Friederici et al., *NeuroReport*, 2009

Source: Bornkessel et al., *NeuroImage*, 2005

Syntax in the human brain



There are two syntactic processing networks

Network 1: Local syntax

- frontal operculum (FOP)
- anterior STG.

Network 2: Complex syntax

- BA 44/45 (Broca's area)
- posterior STG/STS.

Network 1

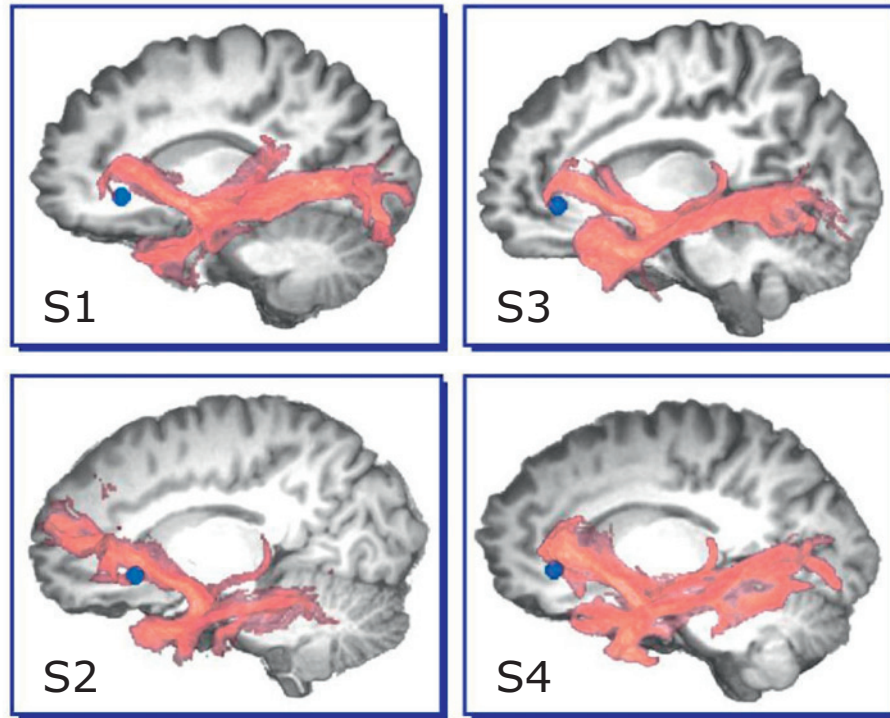
Network 2

Is there additional evidence for two different neural networks?

→ structural connectivity by means of DTI

Connectivity: Network 1

Local phrase structure processing

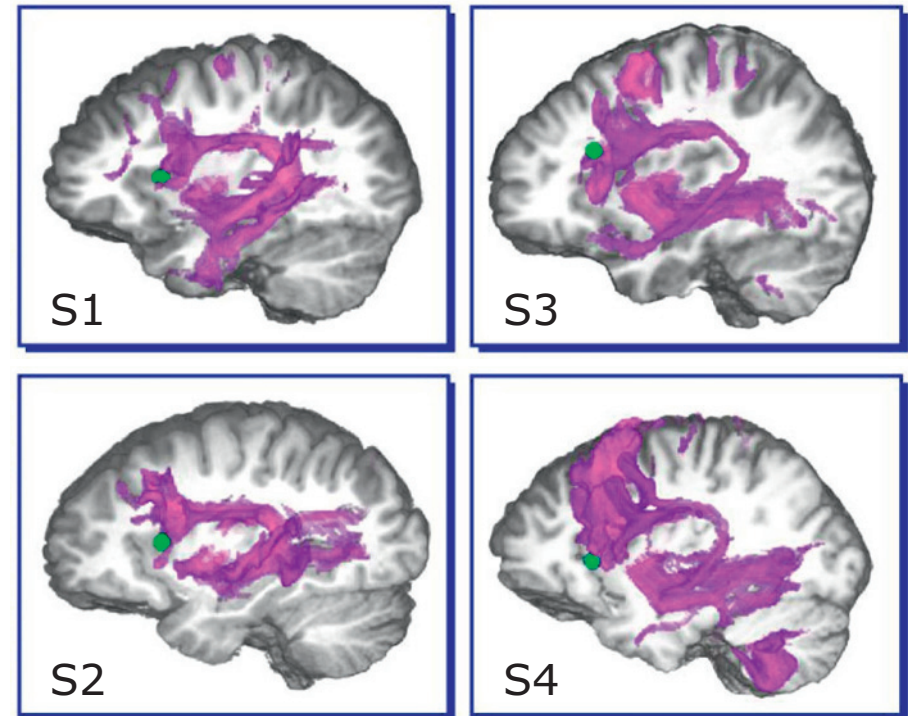


from FOP to STG

ventral pathway

Connectivity: Network 2

Processing complex hierarchy



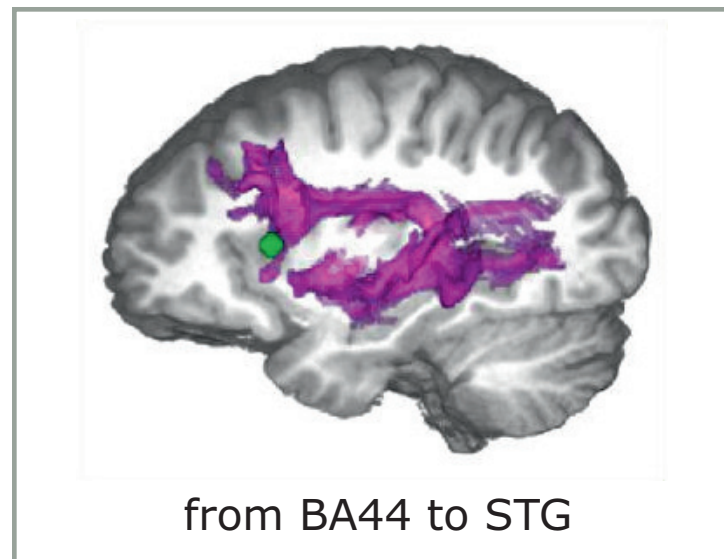
from BA44 to STG

dorsal pathway

● ● individual maximum of activation in functional study

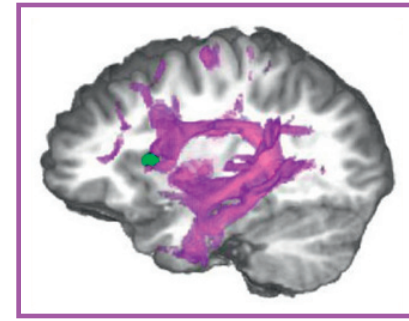
Function of the dorsal pathway: Testing the hypothesis

If the dorsal pathway is responsible for the processing of complex sentences



then this pathway should not yet be fully developed in children at an age when the processing of syntactically complex sentences is still imperfect.

Dorsal pathway & ontogeny



Processing complex sentences in children.

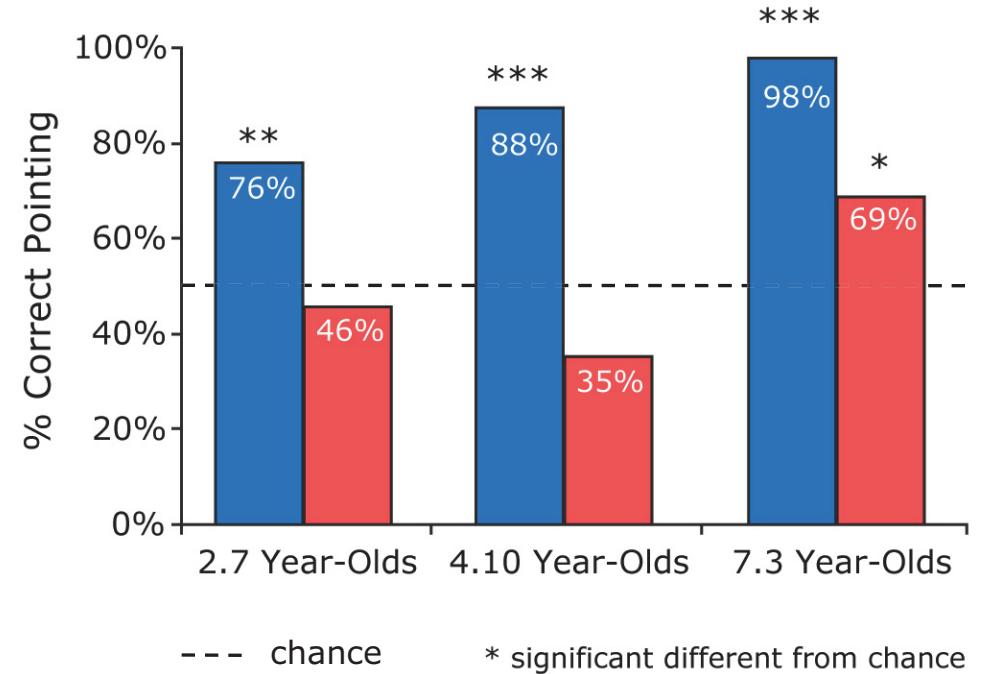
Behavioral evidence

canonical (SVO)

Der Hund wieft den Löwen.
[The dog]_{NOM} is weefing [the lion]_{ACC}.

non-canonical (OVS)

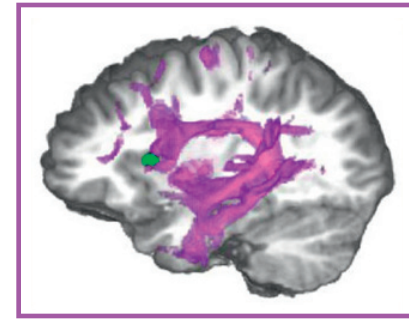
Den Tiger wieft der Bär.
[The tiger]_{ACC} is weefing [the bear]_{NOM}.



Source: Dittmar, Abbot-Smith, Lieven & Tomasello, *Child Development*, 2008

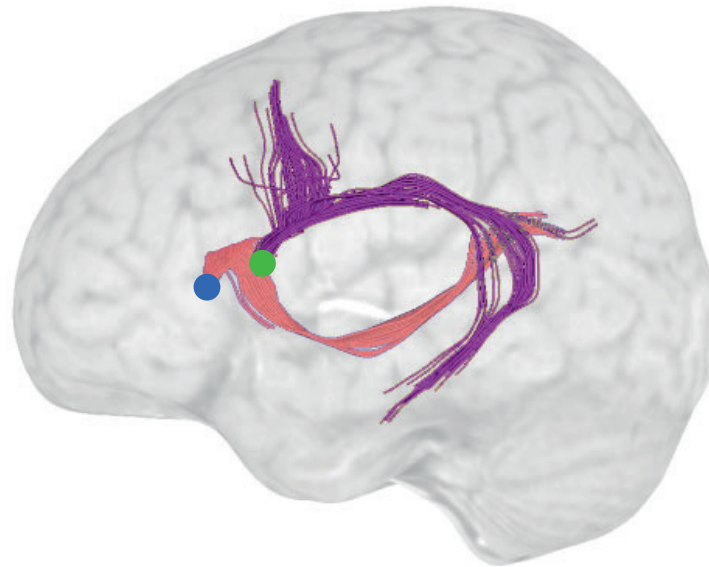
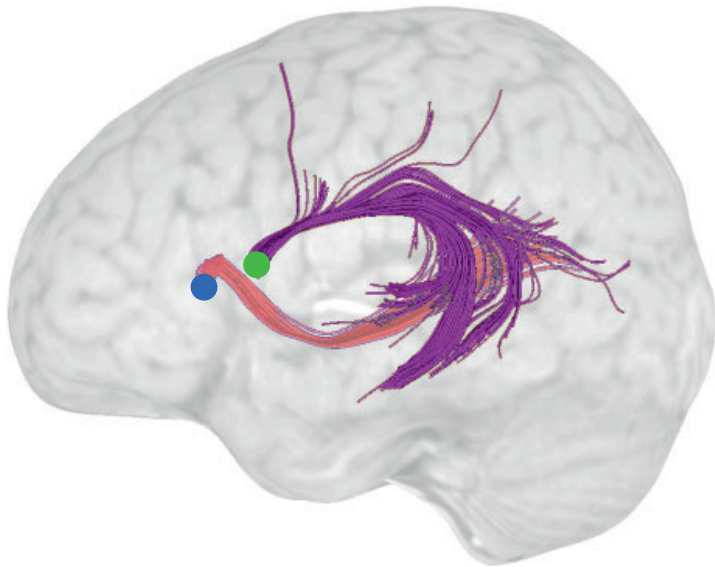
Dorsal pathway & ontogeny

The dorsal pathway is not fully developed in children who still have problems with processing complex sentences.



Adults

7-year-olds



■ dorsal pathway
■ ventral pathway

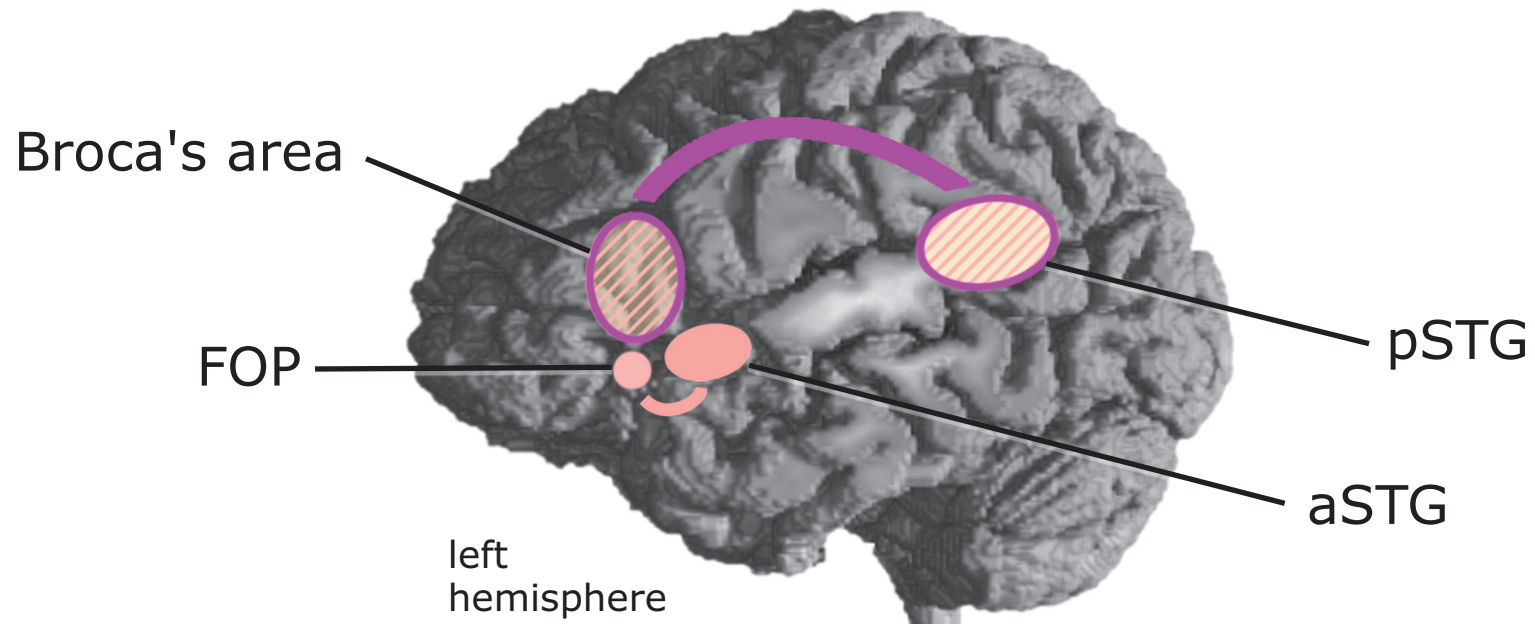
Source: Brauer, Anwander & Friederici, *Cerebral Cortex*, 2010

Lisbon, June 24, 2013

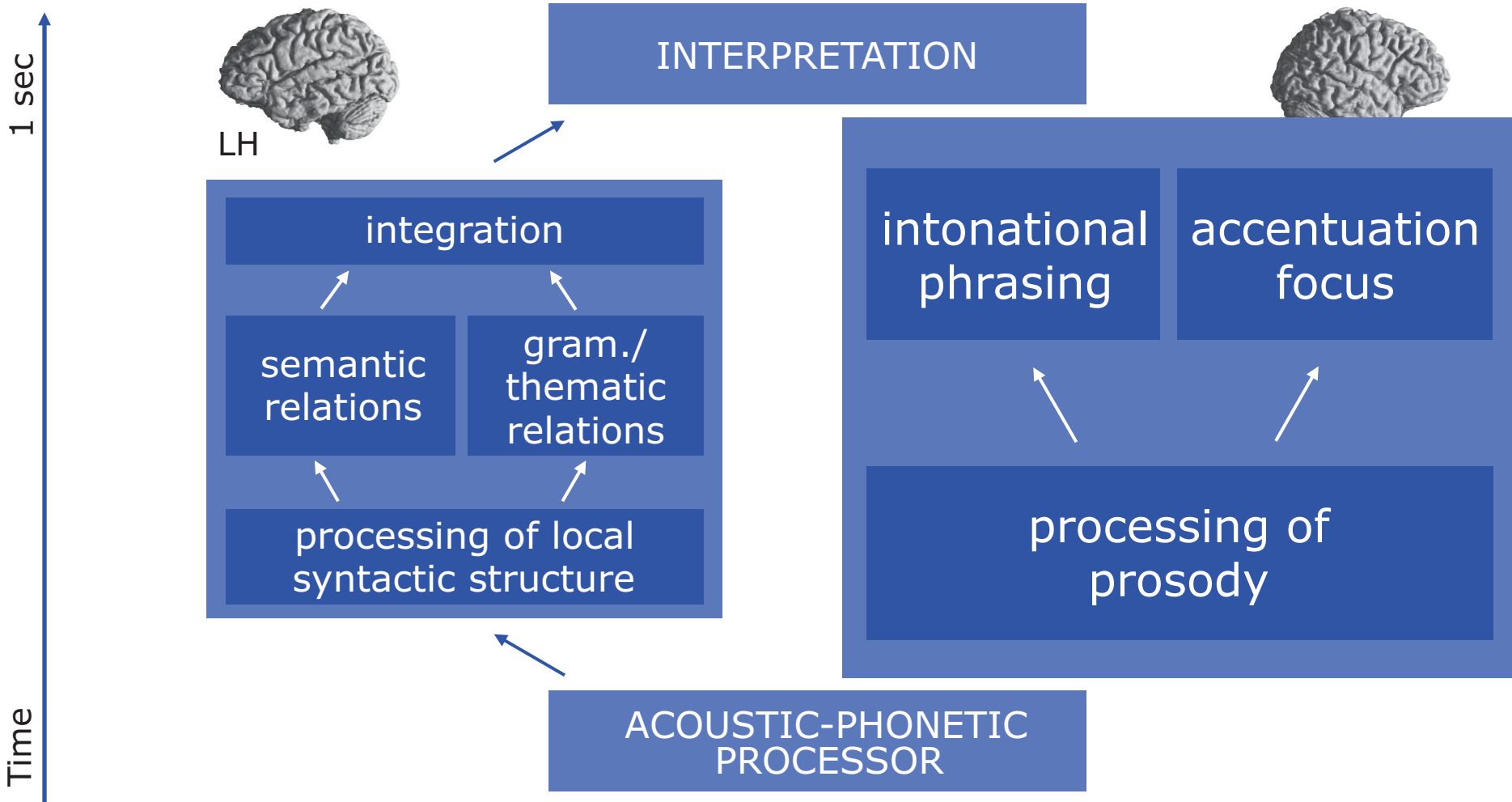
Max Planck Institute for Human Cognitive and Brain Sciences

Conclusion: LH

There are two syntactic networks active during auditory sentence comprehension: One supporting local phrase structure building and one supporting the processing of syntactically complex sentences.



Prosodic processes



Source: Friederici & Alter, *Brain and Language*, 2004

Stimuli: Absence/presence of information type

(1) Normal speech

normal correct sentences containing SEMANTIC, SYNTACTIC and PROSODIC information



(2) Syntactic speech

pseudo word sentences containing SYNTACTIC and PROSODIC information, i.e., lack of semantic info



(3) Prosodic speech (delexicalized)

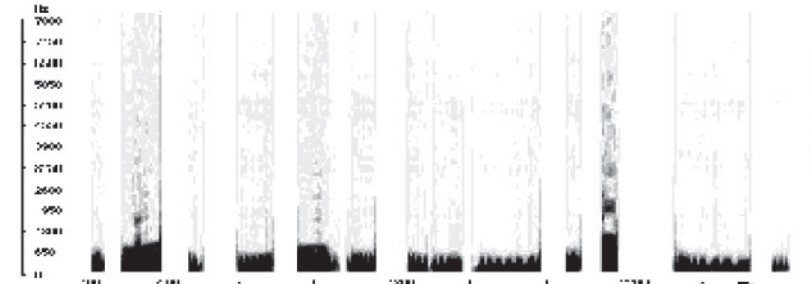
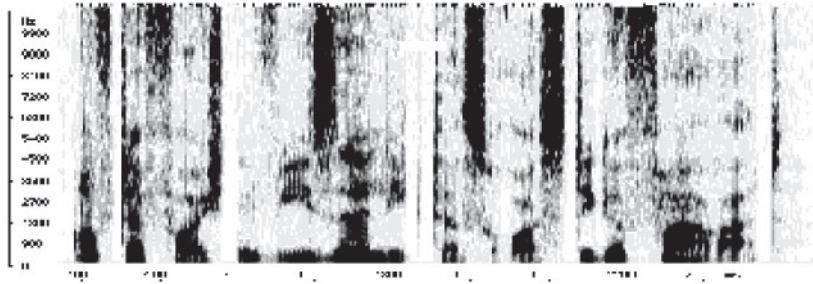
filtered sentences containing PROSODIC information only, i.e., lack of segmental info



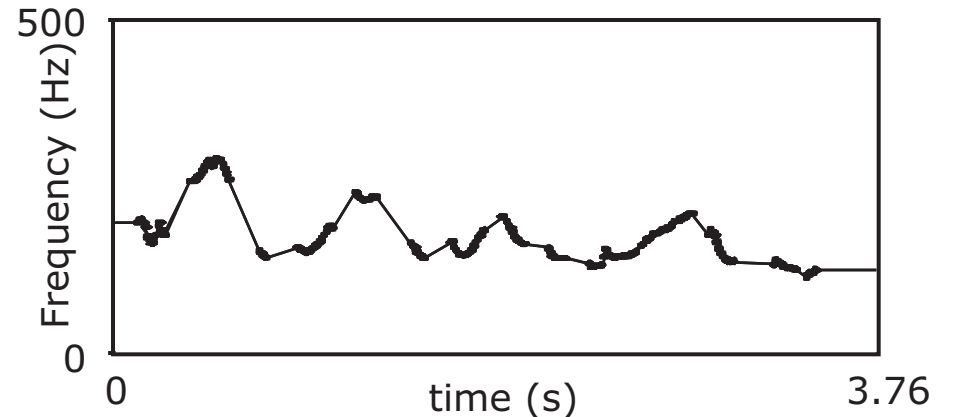
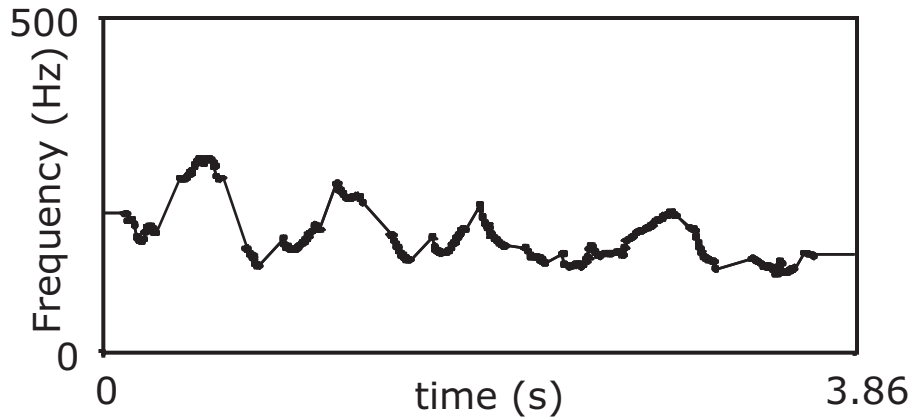
Syntactic speech

Prosodic speech

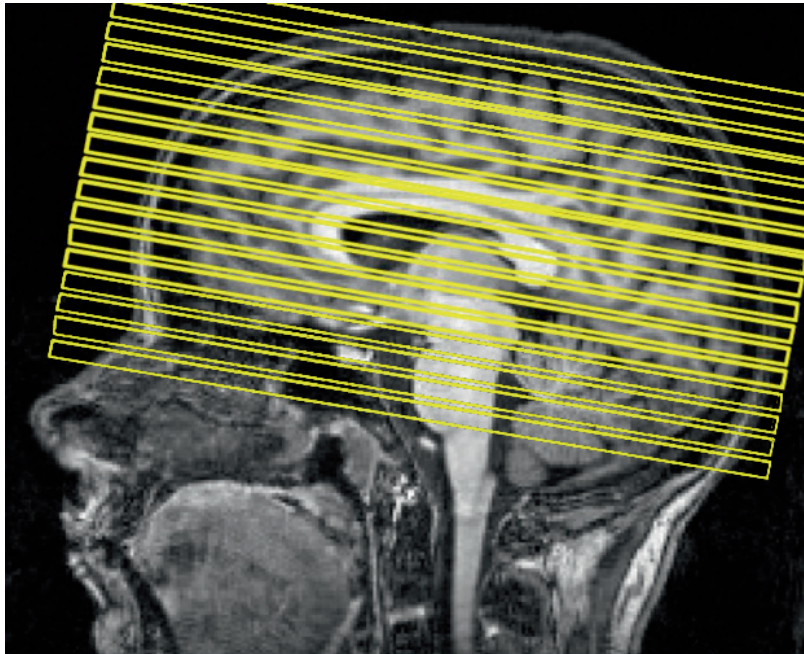
Acoustic signals of stimulus material



Pitch contour



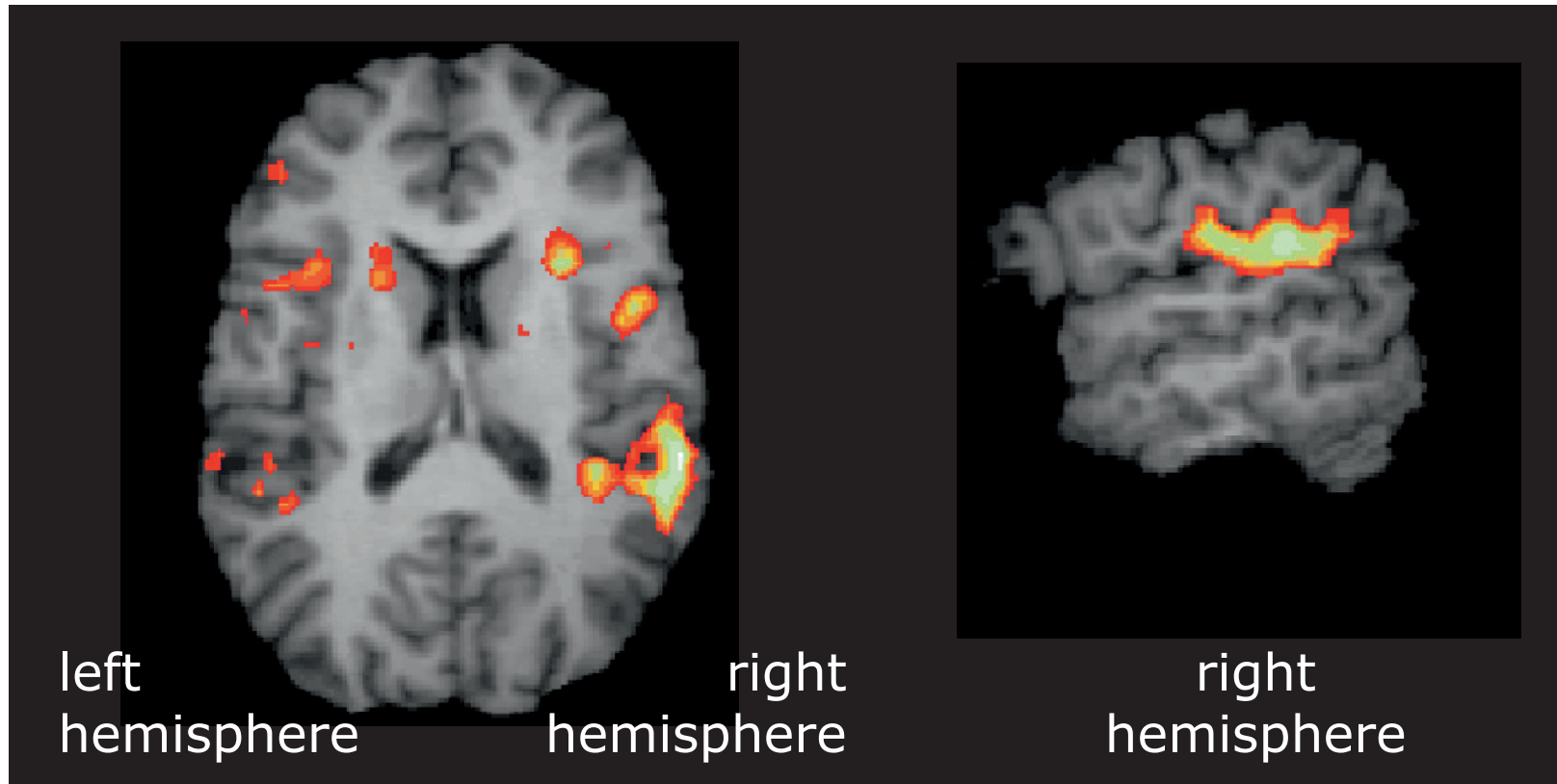
fMRI method



- **MRT:** 3 T Bruker Medspec 30/100 / 3 T Siemens Trio
Anatom. contrasts: T_1 -weighted 3D MDEFT sequence (128 sagittal slices)
Functional contrasts: T_2^* -weighted EPI sequence; TR = 2 s; TE = 40 ms
- **Slices:** horizontal slices parallel to the AC-PC line covering the perisylvian cortex; thickness = 4 mm; skip = 2 mm; 3 mm² *in-plane* and 7 mm *through-plane* resolution.

Prosodic effect

Prosodic speech vs. Syntactic speech



Left: Horizontal slice through the supratemporal plane

Right: Parasagittal view of the right hemisphere

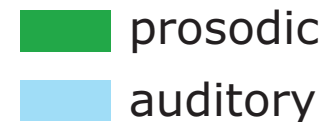
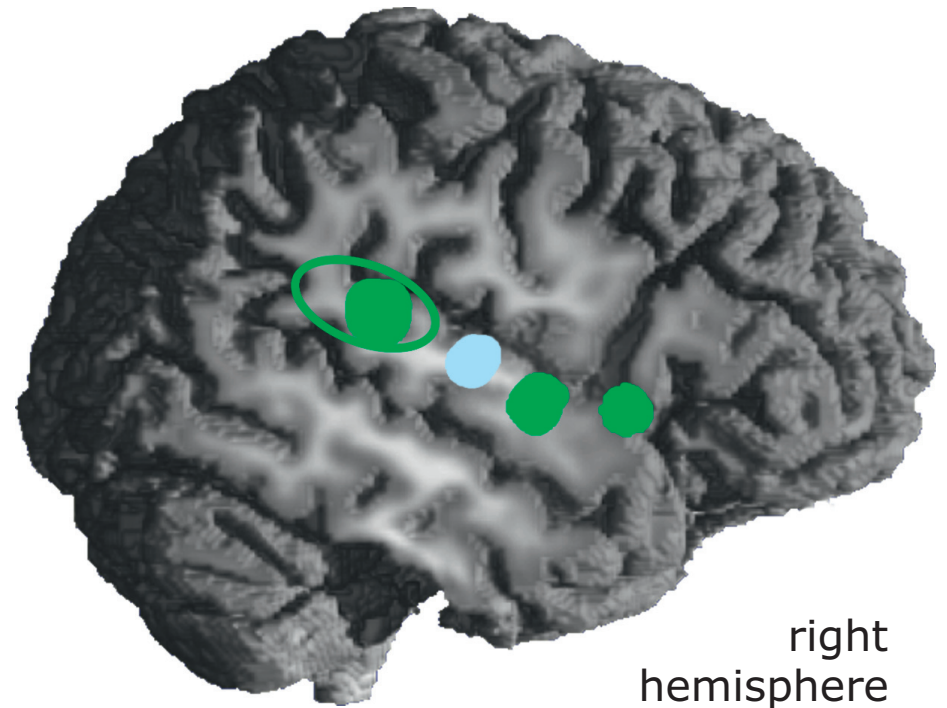
($Z \geq 5$)

Conclusion

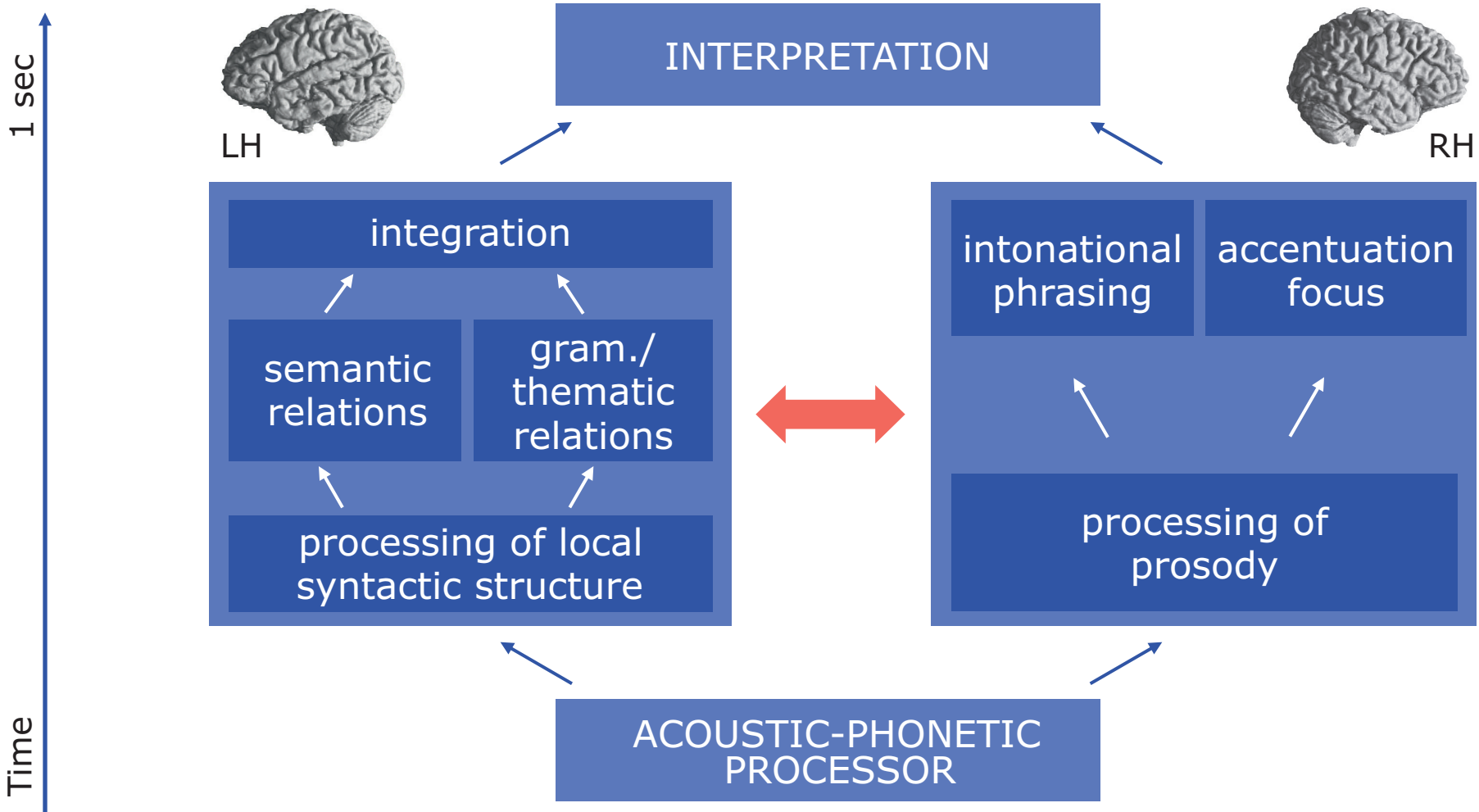
Prosodic processes

are supported in particular by

- opercular portion of the right inferior frontal gyrus
- superior temporal gyrus with dominance in the right hemisphere



Syntax-prosody interaction



Source: Friederici & Alter, *Brain and Language*, 2004

Syntax-Prosody interaction

Since John always jogs a mile
this seems like a short distance to him.

Since John always jogs a mile
seems like a short distance to him.

Syntax-Prosody interaction

[Since John always jogs a mile] #
[this seems like a short distance to him].

Since John always jogs a mile
seems like a short distance to him.

Syntax-Prosody interaction

[Since John always jogs a mile] #
[this seems like a short distance to him].

[Since John always jogs] #
[a mile seems like a short distance to him].

Syntax-Prosody interaction

(A) prosody correct: (1 IP)

[IP1 Peter verspricht Anna zu ARBEITEN] # [IP2 und ...
('Peter promises Anna to work and ...



(B) prosody correct: (2 IP)

[IP1 Peter verspricht] # [IP2 ANNA zu entlasten] # [IP3 und ...
('Peter promises to support Anna and ...



➔ Cross - Splicing:

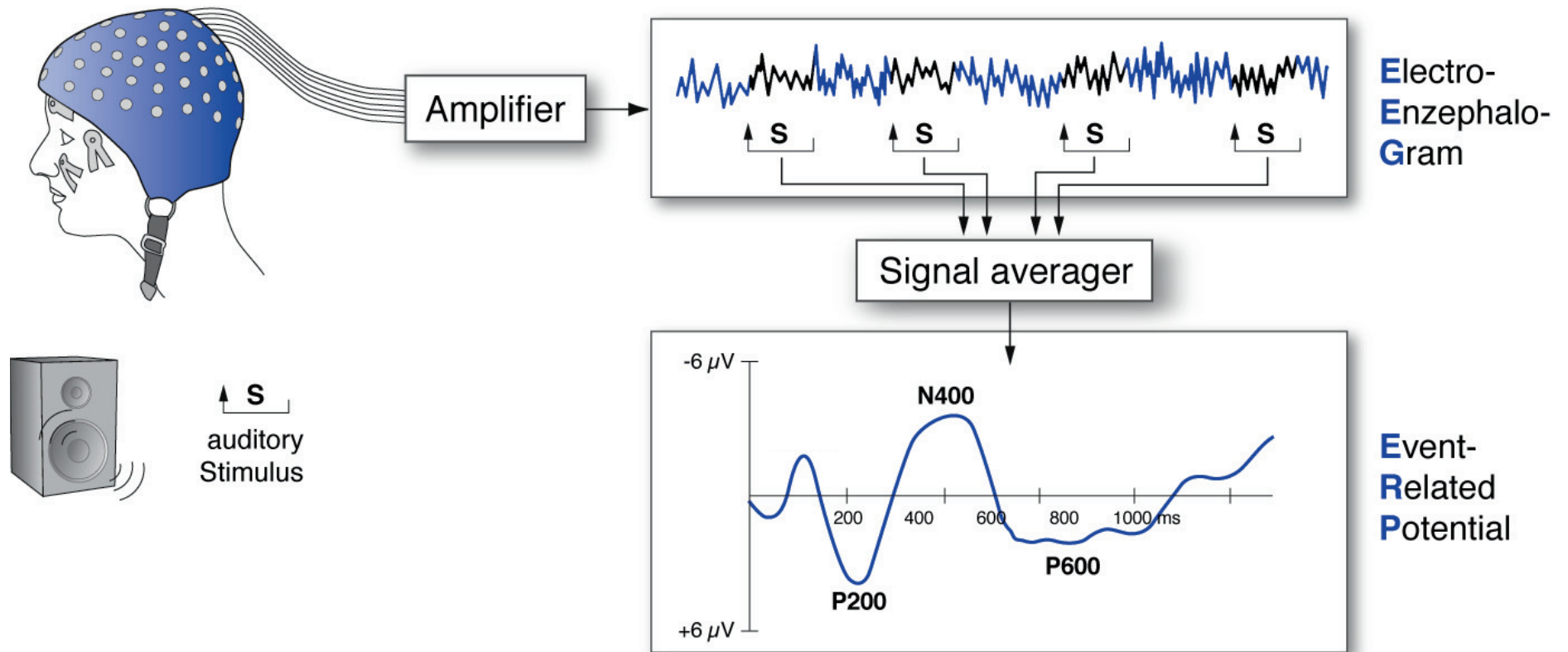
(C) prosody mismatch

*[IP1 Peter verspricht] # [IP2 ANNA zu ARBEITEN] # [IP3 und ...
*('Peter promises to work Anna and ...

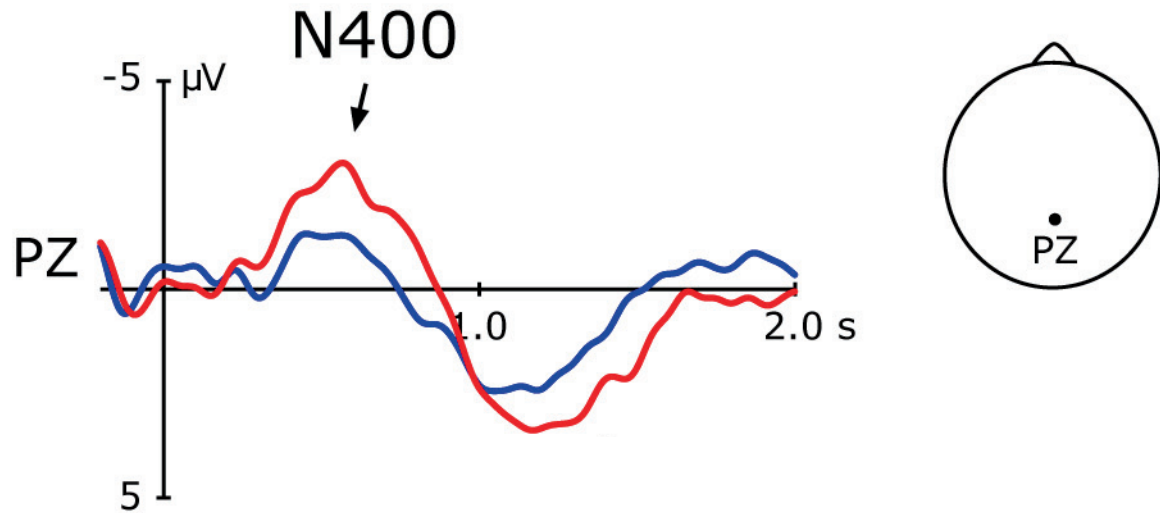


If prosodic information influences syntactic processing, we expect an effect at the critical verb (color coded in yellow).

ERP method is used to identify the prosody mismatch effect



Prosody mismatch effect: Critical verb



prosody correct:

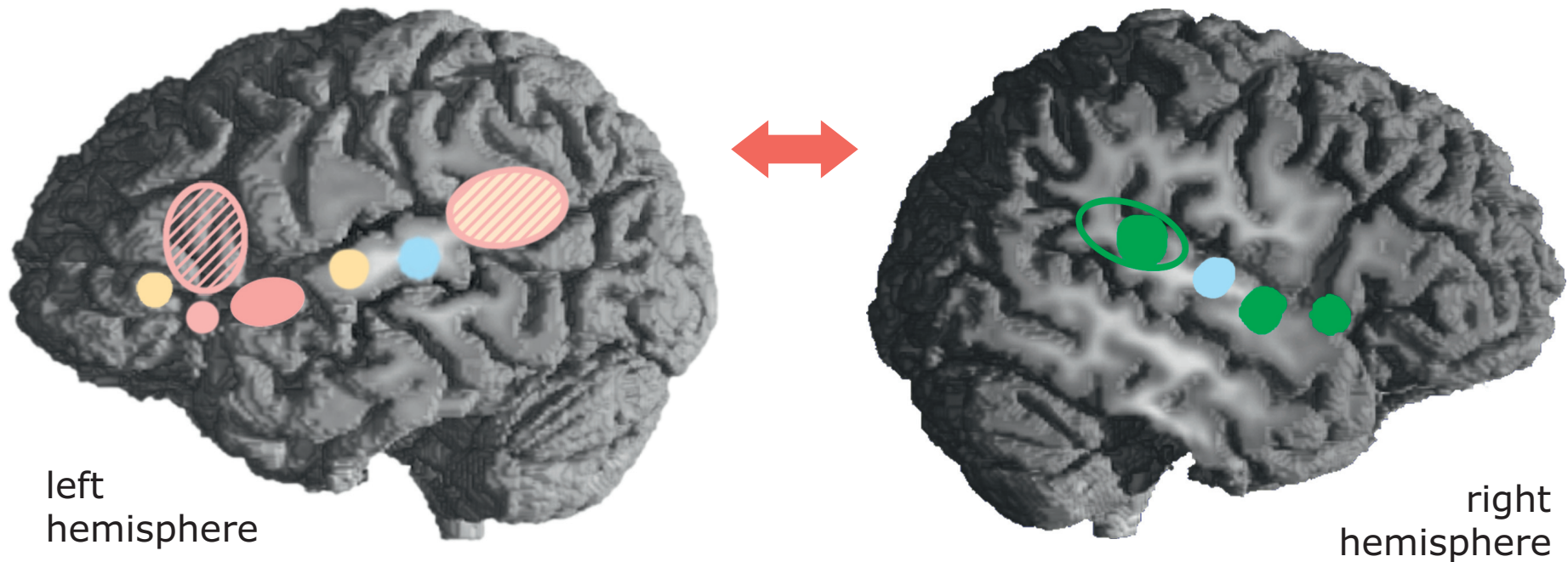
[Peter verspricht] # [Anna zu entlasten] # [und ...

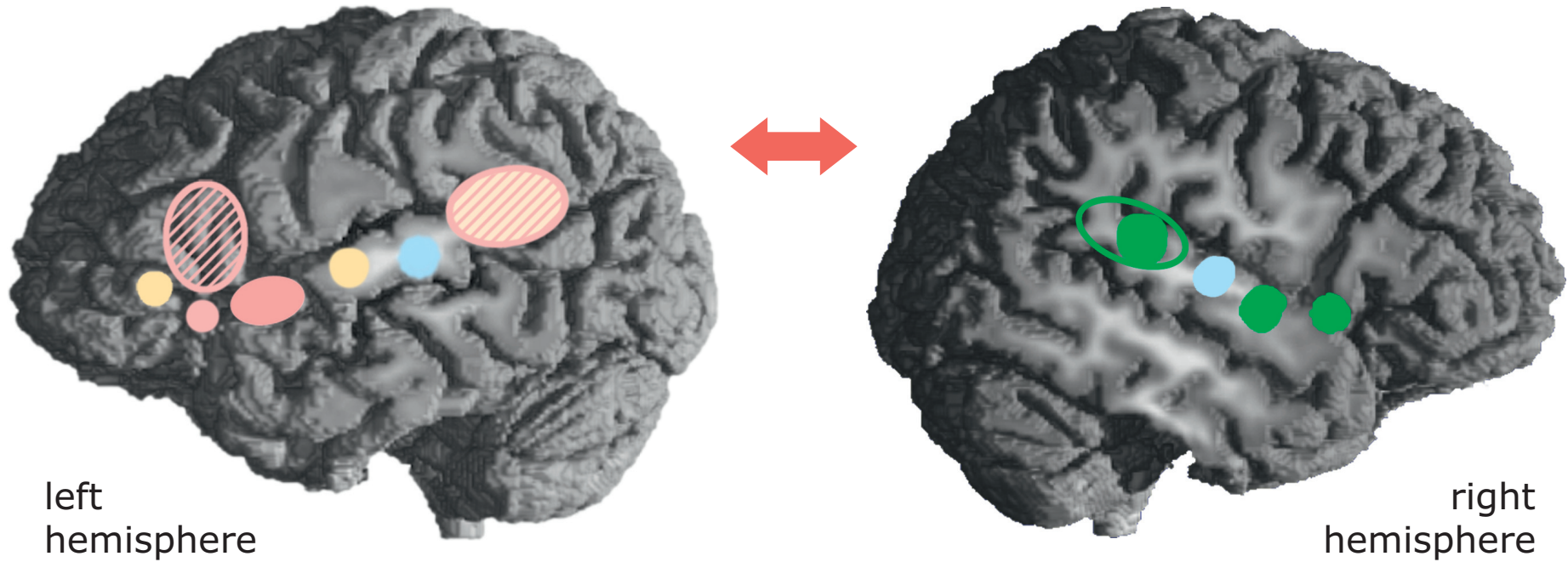
prosody mismatch:

*[Peter verspricht] # [Anna zu arbeiten] # [und ...

Conclusion

Syntactic and prosodic information do interact.

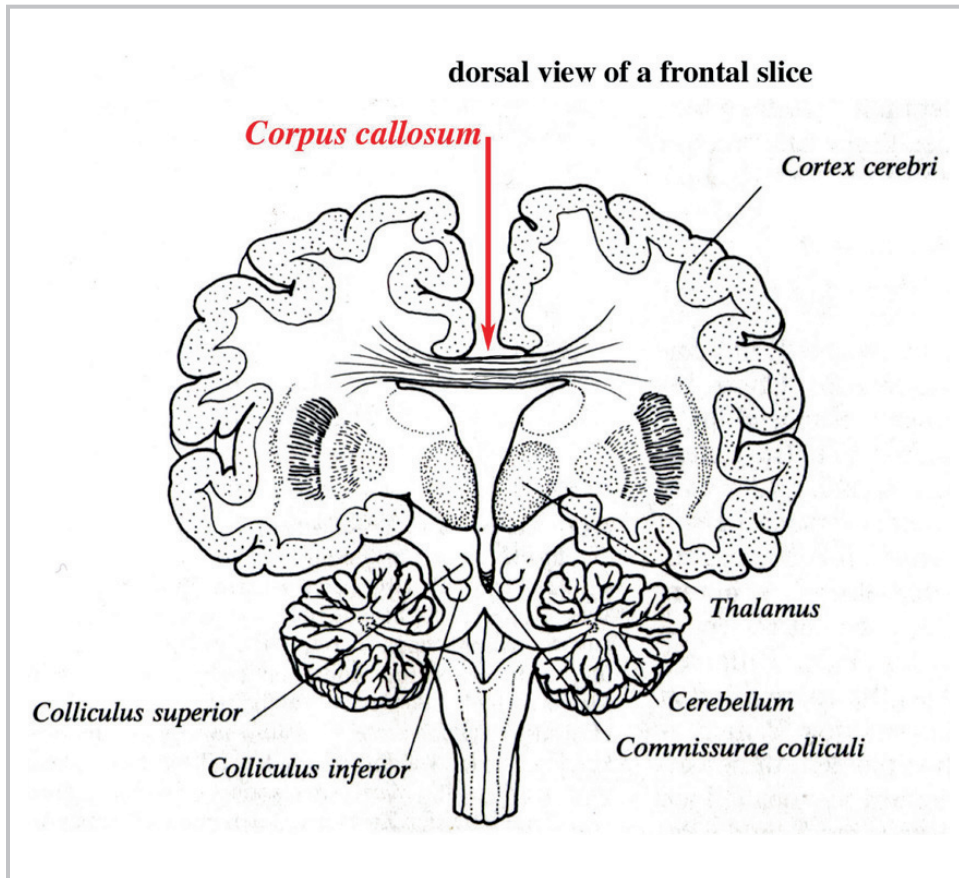




Hypothesis:

Interhemispheric processes may be responsible for the interaction between syntactic and prosodic information.

The Corpus Callosum

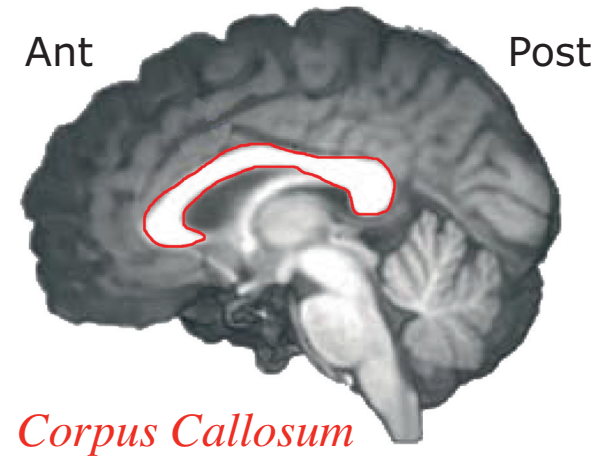
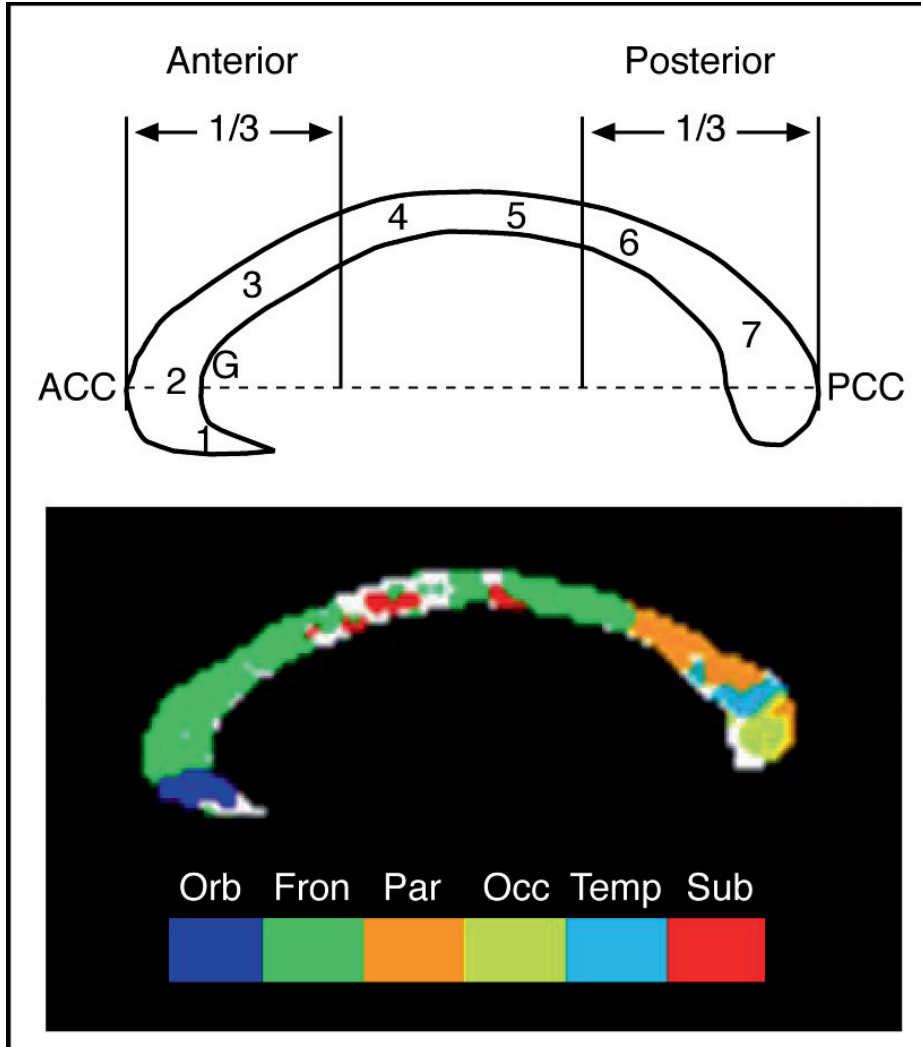


The prediction

If a prosodic mismatch effect at the verb in normal listeners is due to the interaction between LH and RH

→ such an effect should not be observable for patients with lesions in the corpus callosum (CC)

Corpus Callosum and Fiber Projections

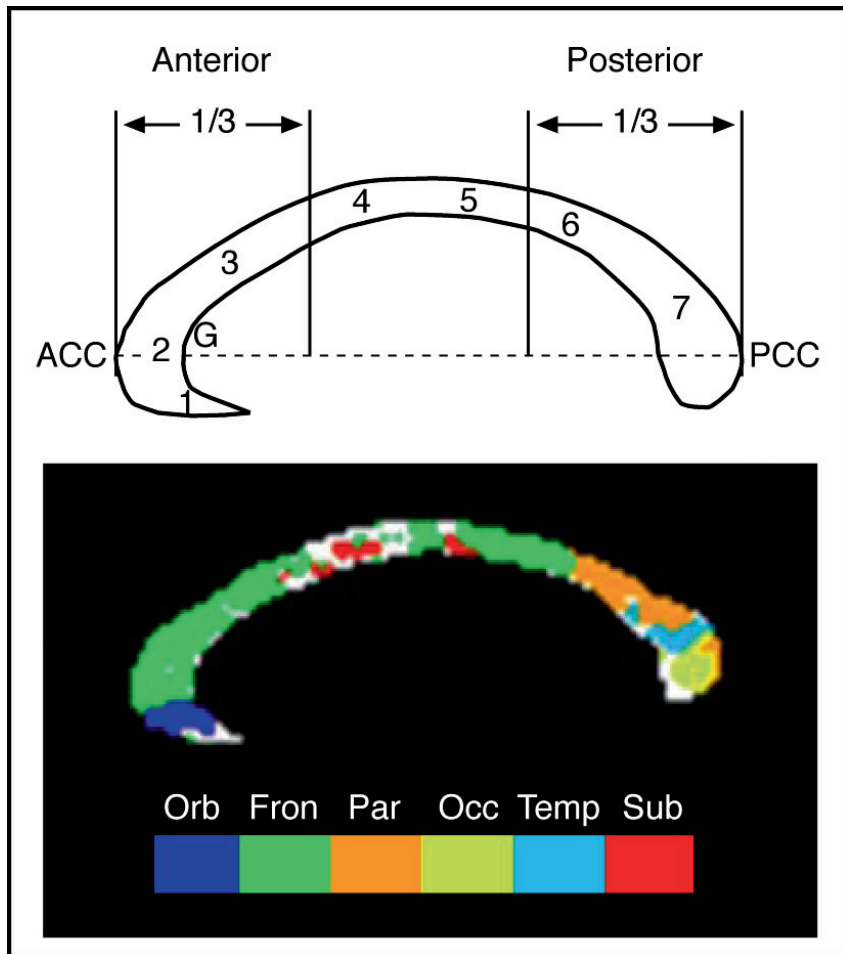


Fibers projecting from one hemisphere to the other

Adapted from: Huang et al., NeuroImage 26, 2005

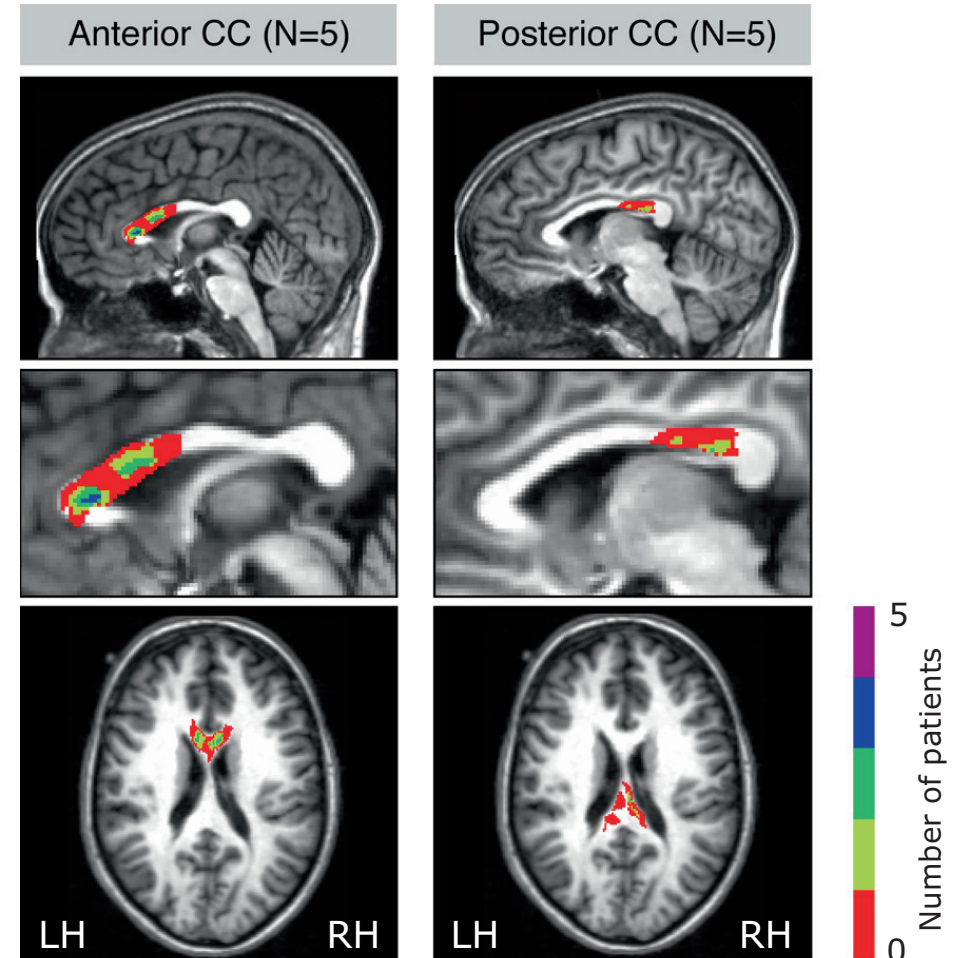
Corpus Callosum and Fiber Projections

Fibers projecting between hemispheres



Adapted from: Huang et al., NeuroImage, 2005

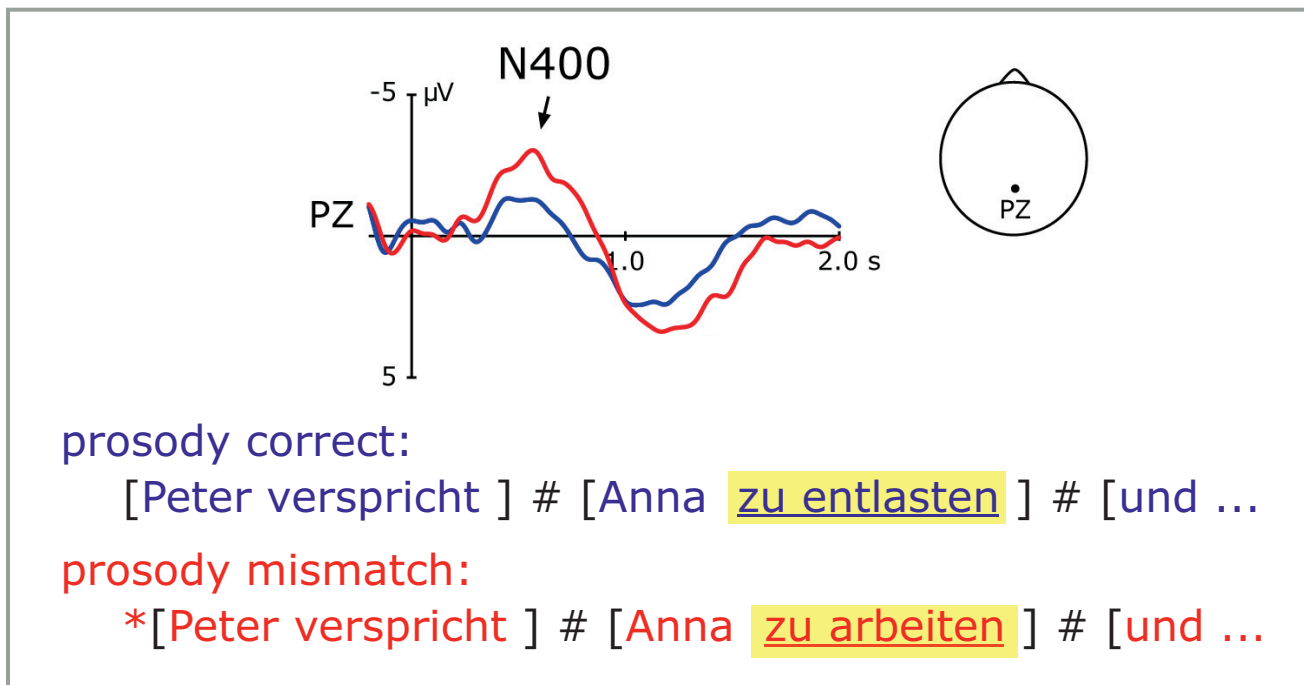
Patients and their lesions in the Corpus Callosum



Source: Friederici, von Cramon, & Kotz, Neuron, 2007

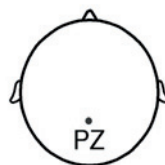
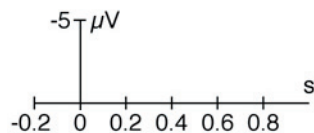
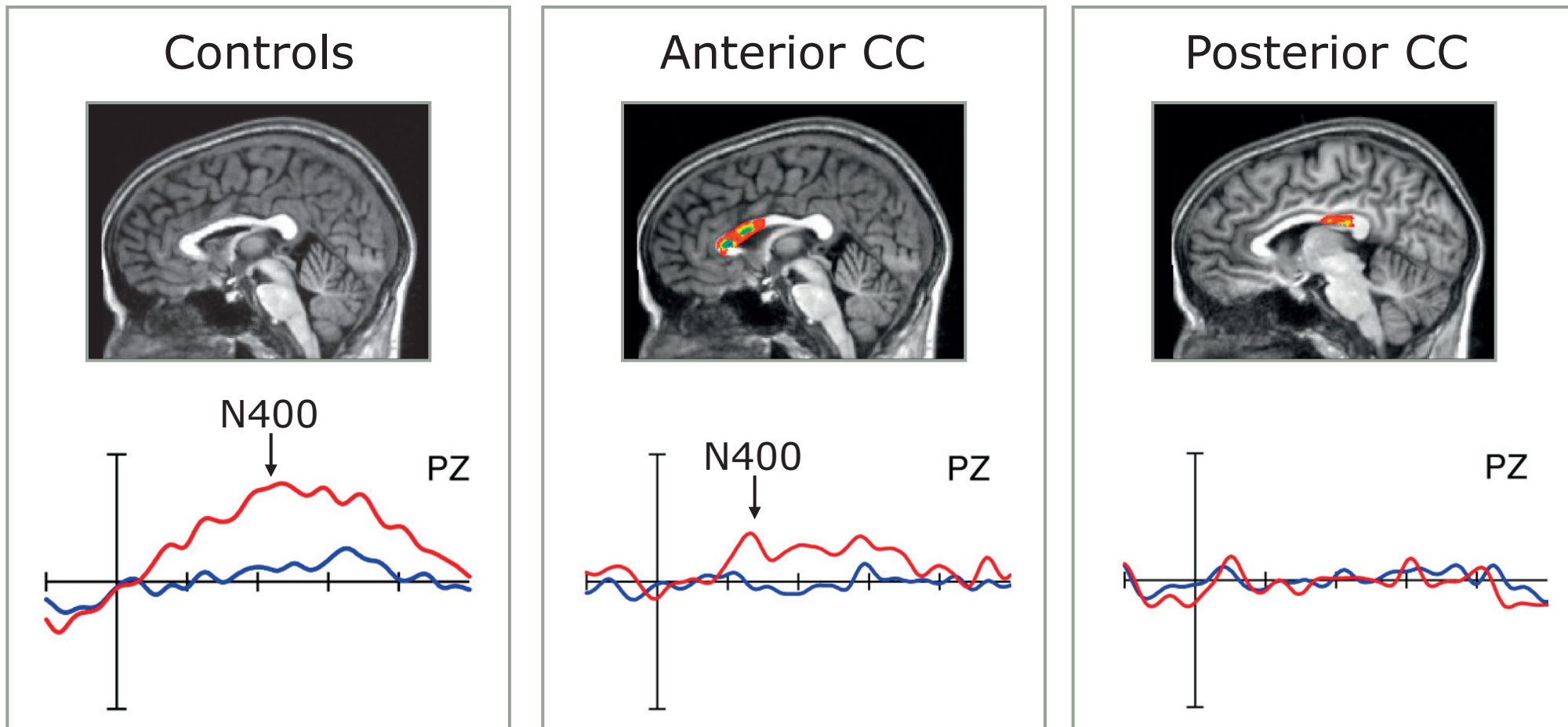
Prediction

If a prosodic mismatch effect at the verb in normal listeners is due to the interaction between LH and RH



→ the prosodic mismatch effect should not be observable for CC patients

Prosody mismatch effect: Critical verb

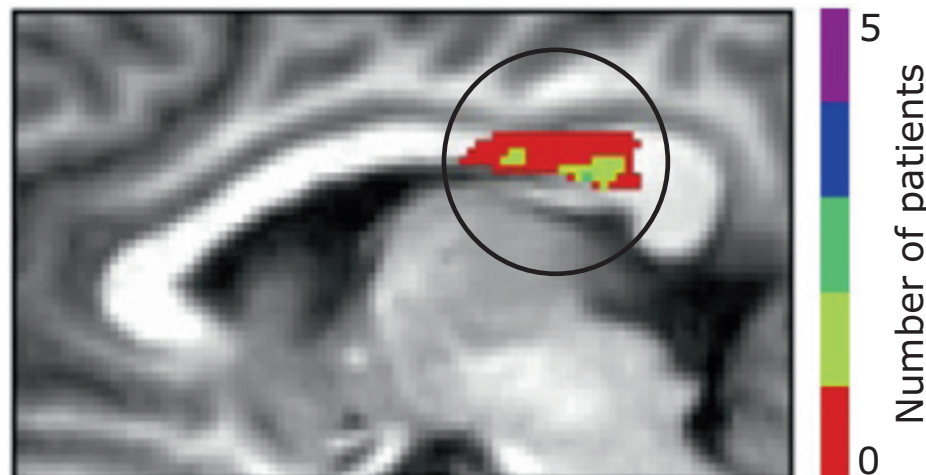
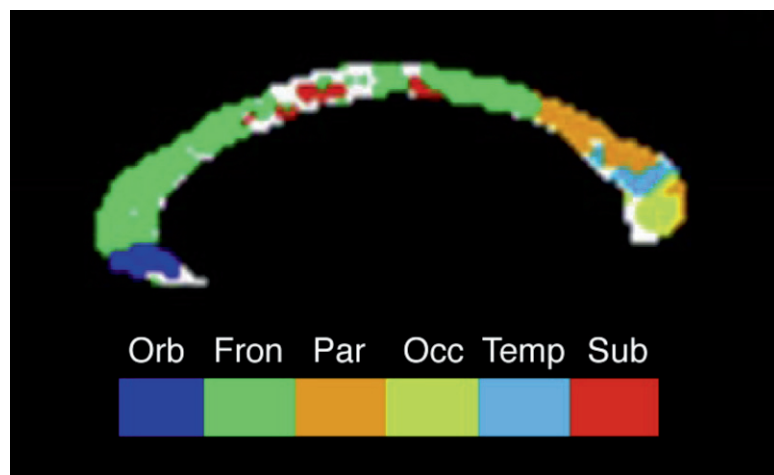


— pros correct
— pros incorrect

Source: Friederici, Kotz & von Cramon, *Neuron*, 2007

Conclusion: CC

The CC plays a crucial role in the interaction of syntactic and prosodic information.



But before this conclusion can be drawn, it must be demonstrated that the posterior CC patients do show an N400 in principle, i.e. when not dependent on prosodic information.

Lexical-semantic N400 Experiment

Stimuli

correct

Das Brot wurde gegessen.

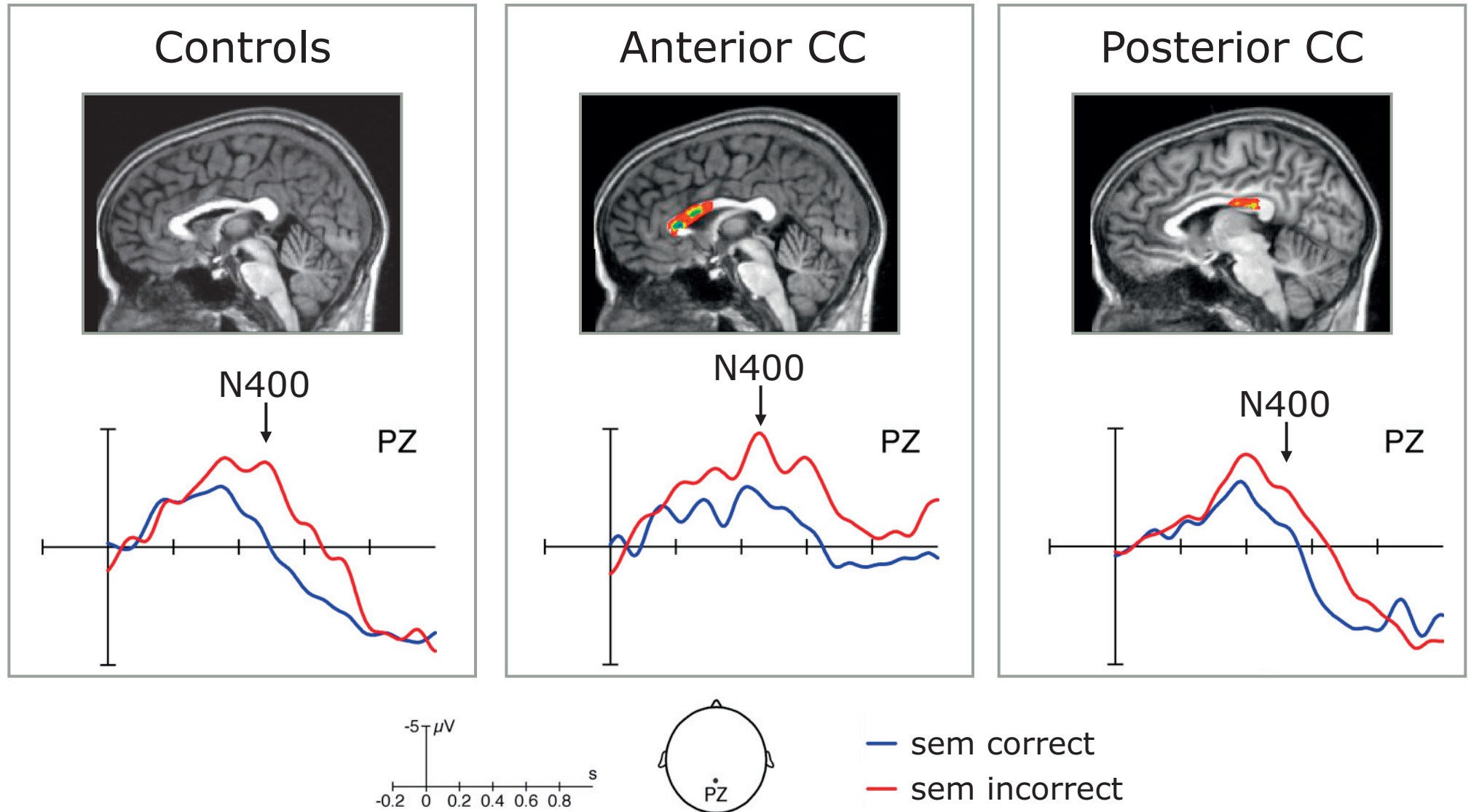
The bread was eaten.

semantically incorrect

Der Vulkan wurde gegessen.

The vulcano was eaten.

Lexical semantic mismatch effect: Critical verb



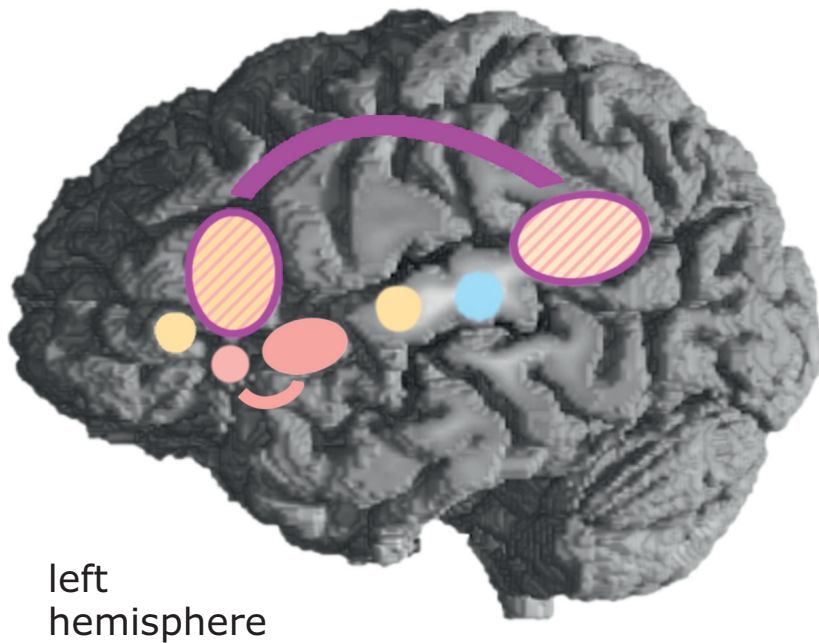
Source: Friederici, Kotz, et al., *Neuron*, 2007

Auditory language comprehension networks

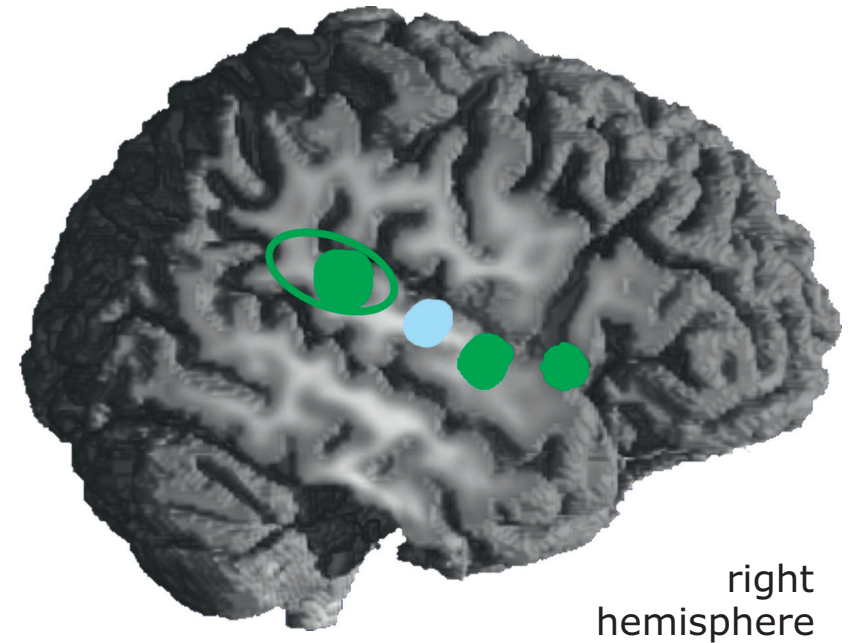
Semantic network in the LH

Two syntactic networks in the LH

Prosodic network in the RH



in CC
interaction



EEG / MEG

Anja Hahne
Björn Herrmann
Burkhard Maess
Yunhua Wang
Karsten Steinbauer

fMRI

Jörg Bahlmann
Ina D. Bornkessel-Schlesewsky
Christian J. Fiebach
Michiru Makuuchi
Martin Meyer
Shirley-Ann Rüschemeyer

Prosody work: Kai Alter

Patient work: Sonja A. Kotz

DTI work: Alfred Anwander

Neuroanatomy: D. Yves von Cramon

MAX
PLANCK
INSTITUTE

FOR
HUMAN
COGNITIVE AND BRAIN SCIENCES

LEIPZIG

