Semantic and syntactic processing in the human brain

Yosef Grodzinsky
Safra Brain Research Center,
Language, Logic and Cognition Center,
Cognitive Science
The Hebrew University of Jerusalem, Israel

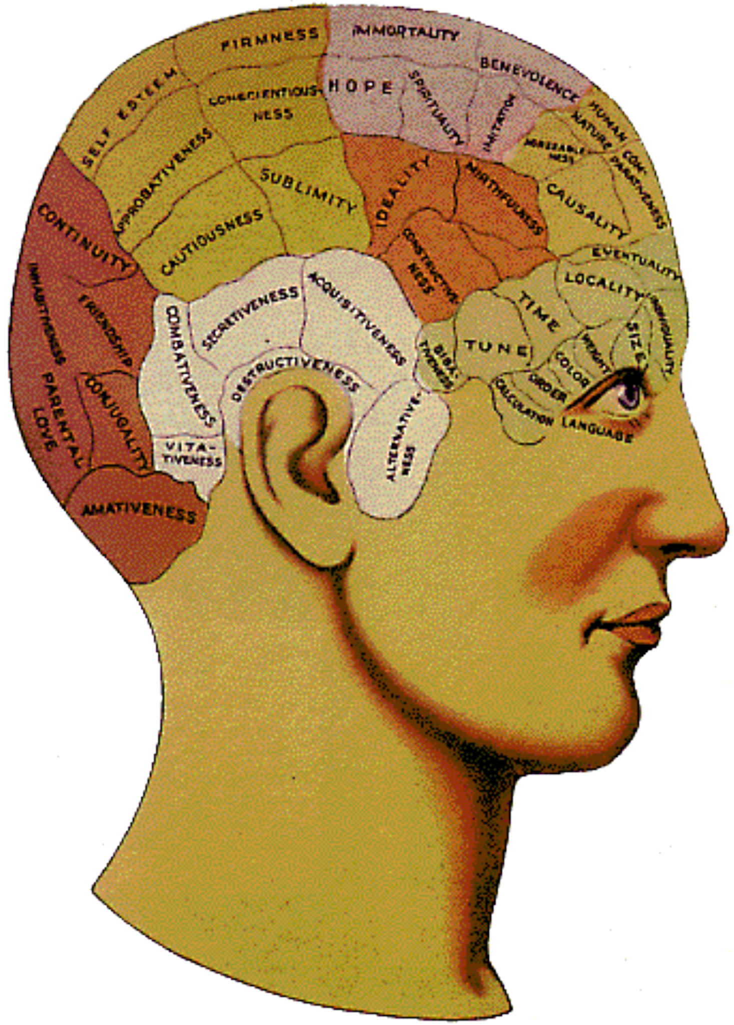
Institute for Neuroscience and Medicine (INM-1)
Forschungszentrum Jülich, Germany

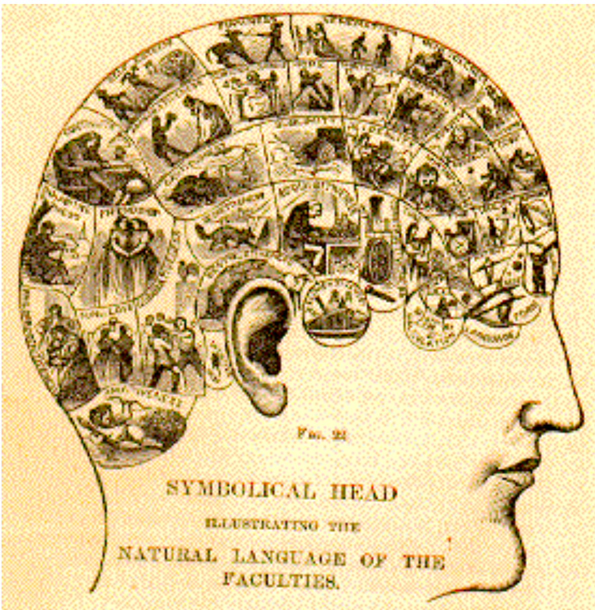
yosef.grodzinsky@mail.huji.ac.il

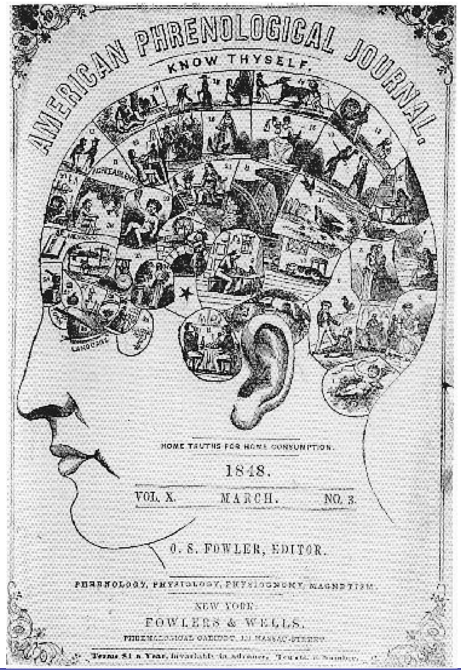
Please do not cite without permission

Franz Joseph Gall

Pieces of our psychology in brain pieces: Gall’s Phrenology and functional localization



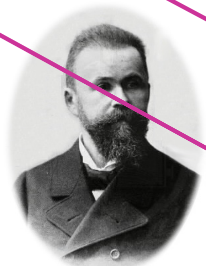




Mapping Principles and their Diagnostic Reflections

production **reception** **naming**

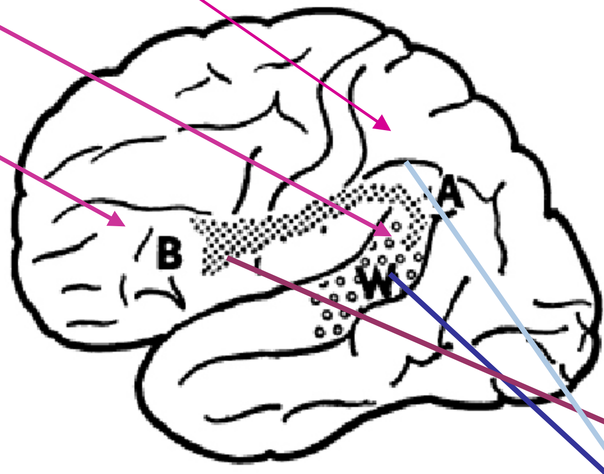
Paul Broca



Carl Wernicke

Norman Geschwind

Take 1



Basis: bedside clinical observations, later codified clinical tests (e.g., *BDAE, WAB*)

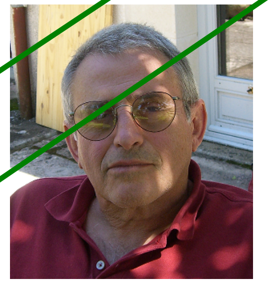
APHASIA

- Nonfluent
  - poor repetition
    - poor comprehension - Global Aphasia
    - good comprehension - Broca Aphasia
  - good repetition
    - poor comprehension - Mixed Transcortical Aphasia
    - good comprehension - Transcortical Motor Aphasia
- Fluent
  - poor repetition
    - poor comprehension - Wernicke's Aphasia
    - good comprehension - Conduction Aphasia
  - good repetition
    - poor comprehension - Transcortical Sensory Aphasia
    - good comprehension - Anomic Aphasia

Geschwind, *Sci.*, 1970; Damasio, *NEJM*, 1992

production **reception**

syntax **semantics**

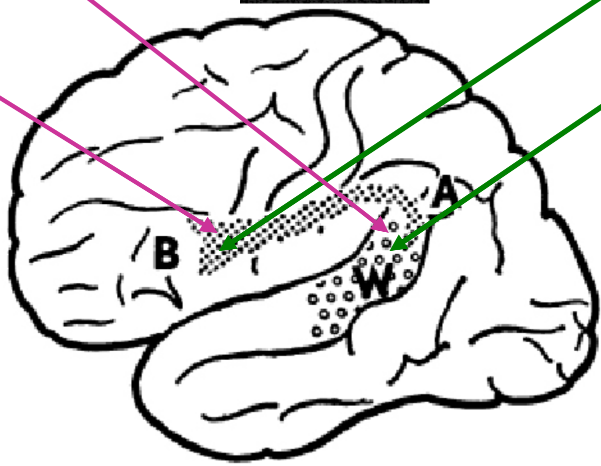


Paul Broca

Carl Wernicke

Take 1

Norman Geschwind



Take 2

Edgar Zurif

Sheila Blumstein

Alfonso Caramazza

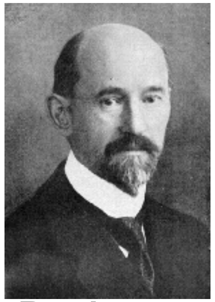
Bedside clinical observations, later codified in The *BDAE, WAB* and related clinical tests

(1) a. The cat that the dog is chasing is brown
    b. The ball that the boy is kicking is red

---

1. *Take 1* and *Take 2* never questioned the *anatomical* modules. Only the *functional* ones were debated, despite the fact that anatomical precision here is dismal.
2. *Take 1* and *Take 2* have both faced major *empirical inconsistencies*
3. *Take 3:* The modules that align with the neurology are *smaller* – they are *pieces of linguistic knowledge* – *components* of syntax, semantics, phonology, etc.
4. *Agenda*: define neurologically viable linguistic pieces, align with *precise anatomy*

Geschwind, *Sci.*, 1970; Blumstein, 1973; Caramazza & Zurif, *Br.Lang.*, 1976


Brodmann


Chomsky

Phrenological beliefs and hopes in our midst:

The anatomist's:

- ***Anatomic modularity***: the brain can be parsed into pieces with *stable and identifiable borders* (***anatomical modules***)

The linguist's:

- ***Grammatical modularity***: linguistic behavior is structured; the principles governing it can be parsed into pieces (***linguistic modules***)

The neurolinguist's:

- ***Meaningful functional anatomy***: linguistic and anatomical modules align

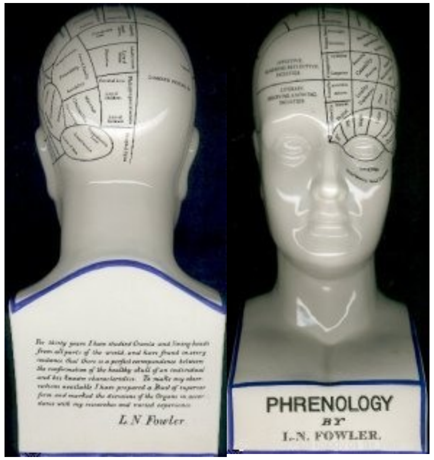
---

The localizationist research agenda:

- identify the linguistic modules and anatomical borders
- Seek alignment between the linguistic and the anatomical

The final punch line:

*Pieces of linguistic knowledge provide the right functional resolution, aligning with cytoarchitectonic borders. We are after **syntax and semantics brain maps***



This mini-course

- *Semantic processing in the brain: how our nervous system deals with the monotonicity of logical operators*

  some logical considerations, followed by multi-modal experimental program with conclusions that might have theoretical implications to compositional semantics

- *Syntactic processing in the brain: the blessing of variability across individual brains and across languages and individuals speakers*

  some anatomical considerations and techniques, with neurolinguistic studies of syntax that focus on variability

Semantic processing in the brain: how our nervous system deals with the monotonicity of logical operators

1. Semantic processing in the brain: how our nervous system deals with the monotonicity of logical operators

- *Goal*

  To gain insights on the structure, and the temporal and neural dynamics of quantification

- *Agenda*

  - To look for the processing signature of quantifier monotonicity
  - To test the modularity hypothesis in the context of quantifiers and quantities
  - To study the neural dynamics of these processes

Today's menu

1. Quantifier polarity in brain & behavior
2. Polarity and sentence verification
3. Heim's "little" and comparatives:
   an experimental perspective

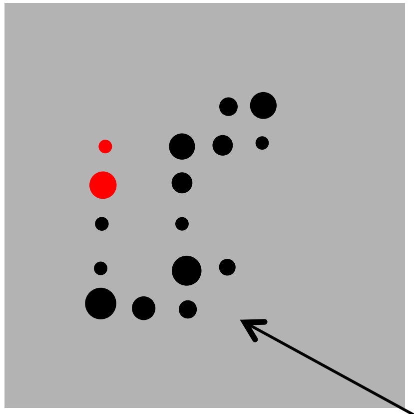
Experimental Paradigm

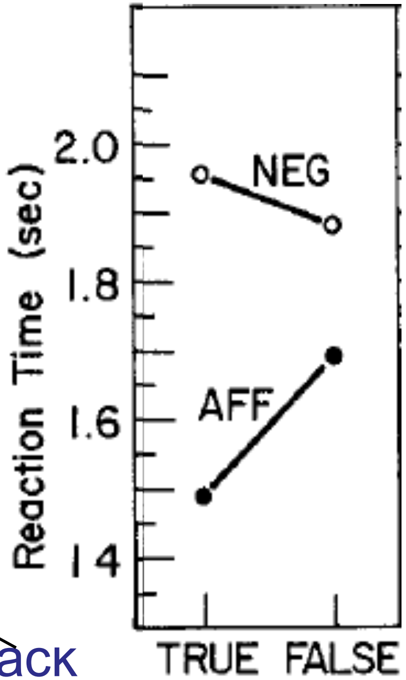
Verification with quantifiers and non-linguistic symbols

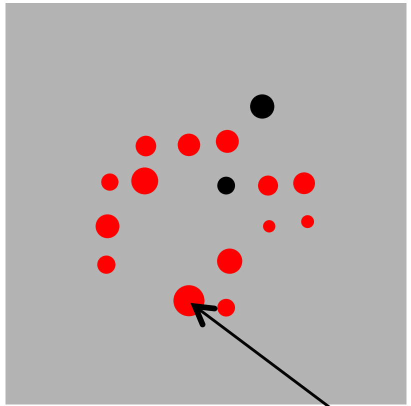
Multi-Modal Measurements

RT, errors in aphasia, fMRI signal intensity

Verification with degree quantifiers and numerosity-containing scenarios







(1) a. **Many** of the dots are black

b. **Few** of the dots are red

J&C:

- *Decomposition*

  Many dots are red

  Neg(many) dots are red

- *Fixed verification strategy*

  Focus on larger set of objects in image

  Focus on larger set

*Arguments for J&C's view on negation in **few**:*
negative quantifiers behave as it they contain a covert negation

Negation-containing operators license Negative Polarity Items

(2) a. ***All** of the students *ever*$_{NPI}$ climbed Mount Everest

b. **None** of the students *ever*$_{NPI}$ climbed Mount Everest

Quantifiers of degree and proportion replicate this pattern

(3) a. ***Many** of the students *ever*$_{NPI}$ climbed Mount Everest

b. **Few** of the students *ever*$_{NPI}$ climbed Mount Everest

(4) a. **All** of the students worked hard ⇒ **All** of the students worked

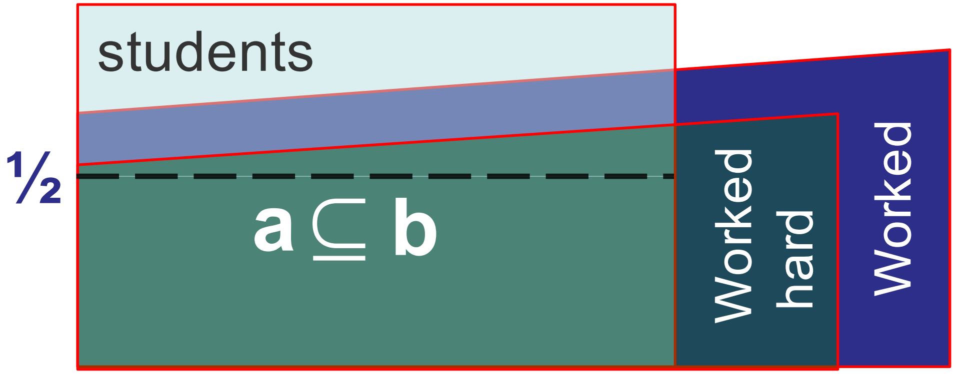
b. **None** of the students worked ⇒ **None** of the students worked hard

Klima, 1964; Fauconier, 1975; Ladusaw, 1980

More: negative quantifiers reverse entailment patterns

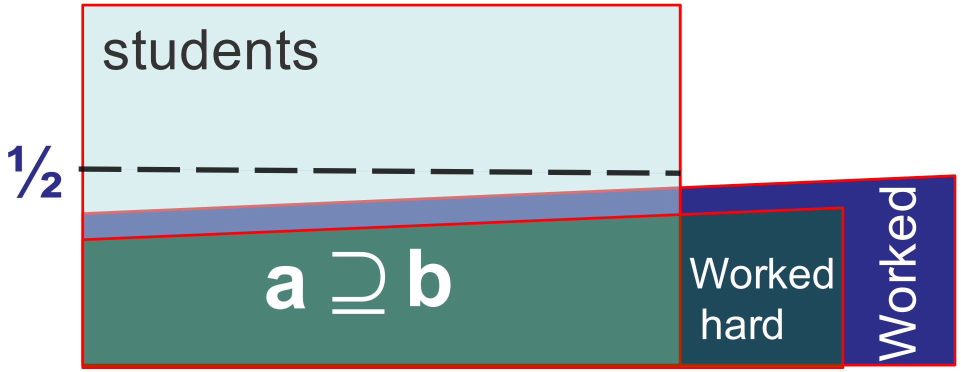
(5) *Positive quantifiers – from subsets to supersets (Monotone-↑):*

a. **>½** of the students worked hard ⇒ b. **>½** of the students worked



(6) *Negative quantifiers – from supersets to subsets (Monotone-↓):*

a. **<½** of the students worked hard ⇐ b. **<½** of the students worked



Defining entailment in set theoretic terms

(7) **Sentence entailment**

- S1 entails S2, S1 $\Rightarrow$ S2, if and only if every situation in which S1 holds is a situation in which S2 holds.
- {s: S1 holds in s} $\subseteq$ {s: S2 holds in s}

(8) **VP entailment**

- VP1 entails VP2, VP1 $\Rightarrow$ VP2, if and only if every individual of which VP1 holds is an individual of which VP2 holds.
- {x: VP1 holds of x} $\subseteq$ {x: VP2 holds of x}

Conclusions so far

- *Few behaves as if it contains a covert negation*
- *Few is processed more slowly than many*

questions

- Is the processing effect specific to *many/few*? generality of effect
- Is it specific to language? specificity
- If subjects focus on the larger set, does its (relative) size matter? perceptual-linguistic interactions
- What is the source of the contrast? Is it really covert **negation**?

A self-guided multi-modal experimental journey

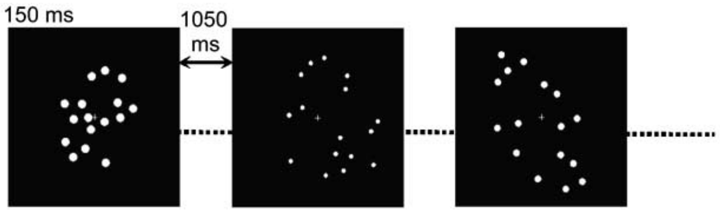
- *1. extend the scope of behavioral results*
- *2. use the behavioral results as a guide for a fMRI investigation*
- *3. corroborate fMRI results with lesion-based*

Hope

1. *Results will reveal something important about functional anatomy – how how the monotonicity of logical operators is neurally computed.*
2. *They will teach us something important about the relevant function*

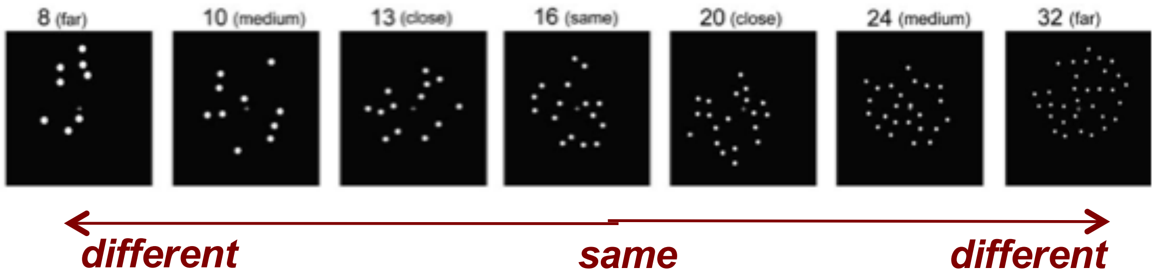
Verification in the context of quantities: an example from numerical cognition

a. Stream of habituation of *r*eference stimuli



r=16

b. Occasional deviant *C*omparandum stimulus of varying numerosity



C=8,…32

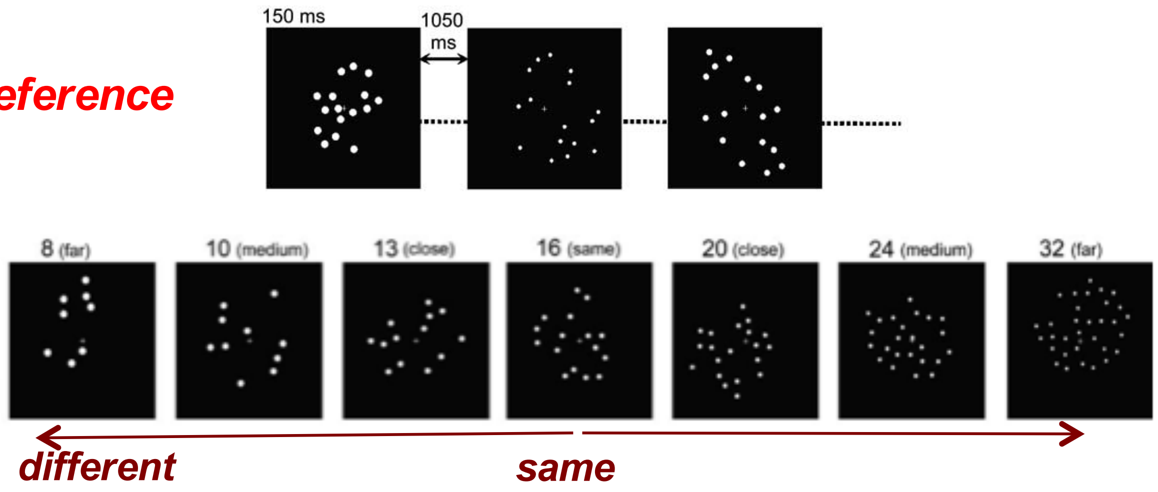
c. Instructions: *indicate whether the fourth set was*
(global)
- larger or smaller than the preceding ones
- same as the preceding ones
- different from the preceding ones

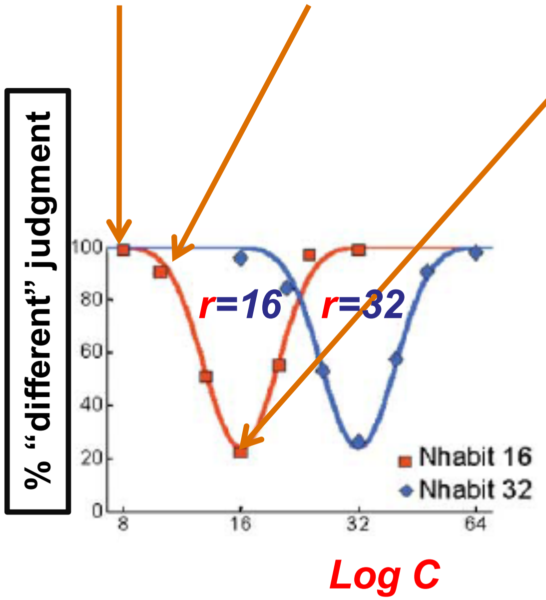
d. Expectations: *- perfomance in keeping with Weber's Law*
- no effect of instructions on performance: r>c=c<r

An example experiment

***r**eference*

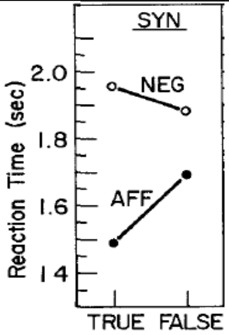
***C**omparanda*





Results:

- Performance is a non-monotone function of ***r***/***c*** proportion
- Best fit to symmetrical curves is obtained after log compression
- Similar σ across ***r***-values
- no reported effect of instruction probes on performance



But instructions DO matter. So:

- An attempt to reproduce J&C's result with different quantifier pairs <*many*, *few*>; <*more-than-half*, *less-than-half*>
- An attempt to generalize to *r/c* proportions beyond 2:14, 14:2
- A comparison with parallel non-linguistic instructions (**<**, **>**)

An RT experiment with the Parametric Proportion Paradigm (PPP)

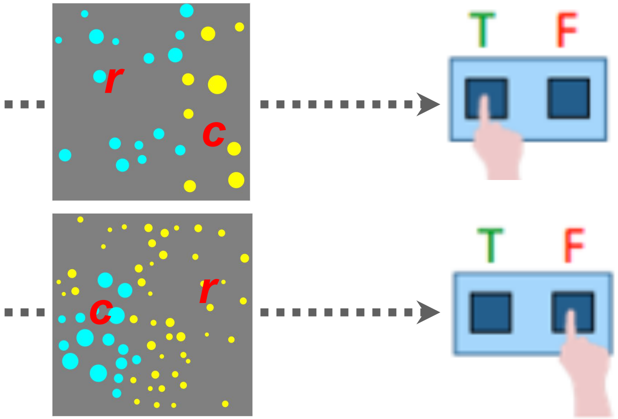
(with Isabelle Deschamps, McGill. Galit Agmon & Yonatan Loewenstein, HUJI)

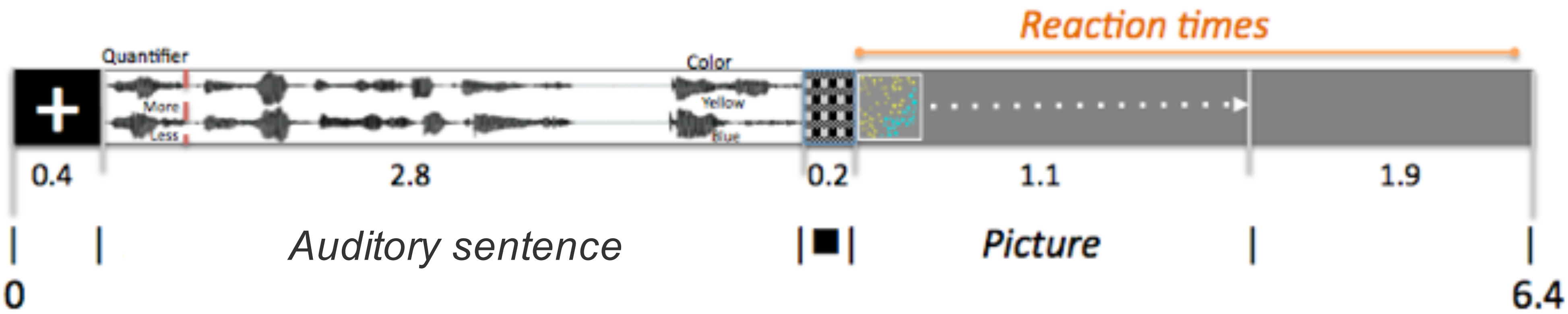
POS:

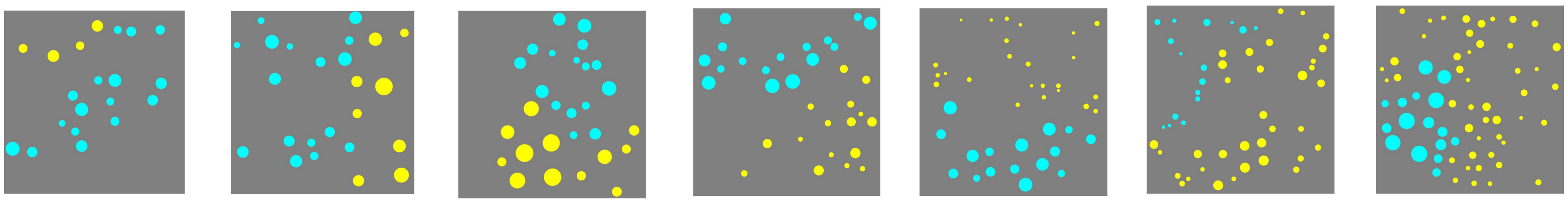
More-than-half of the circles are blue

NEG:

Less-than-half of the circles are yellow

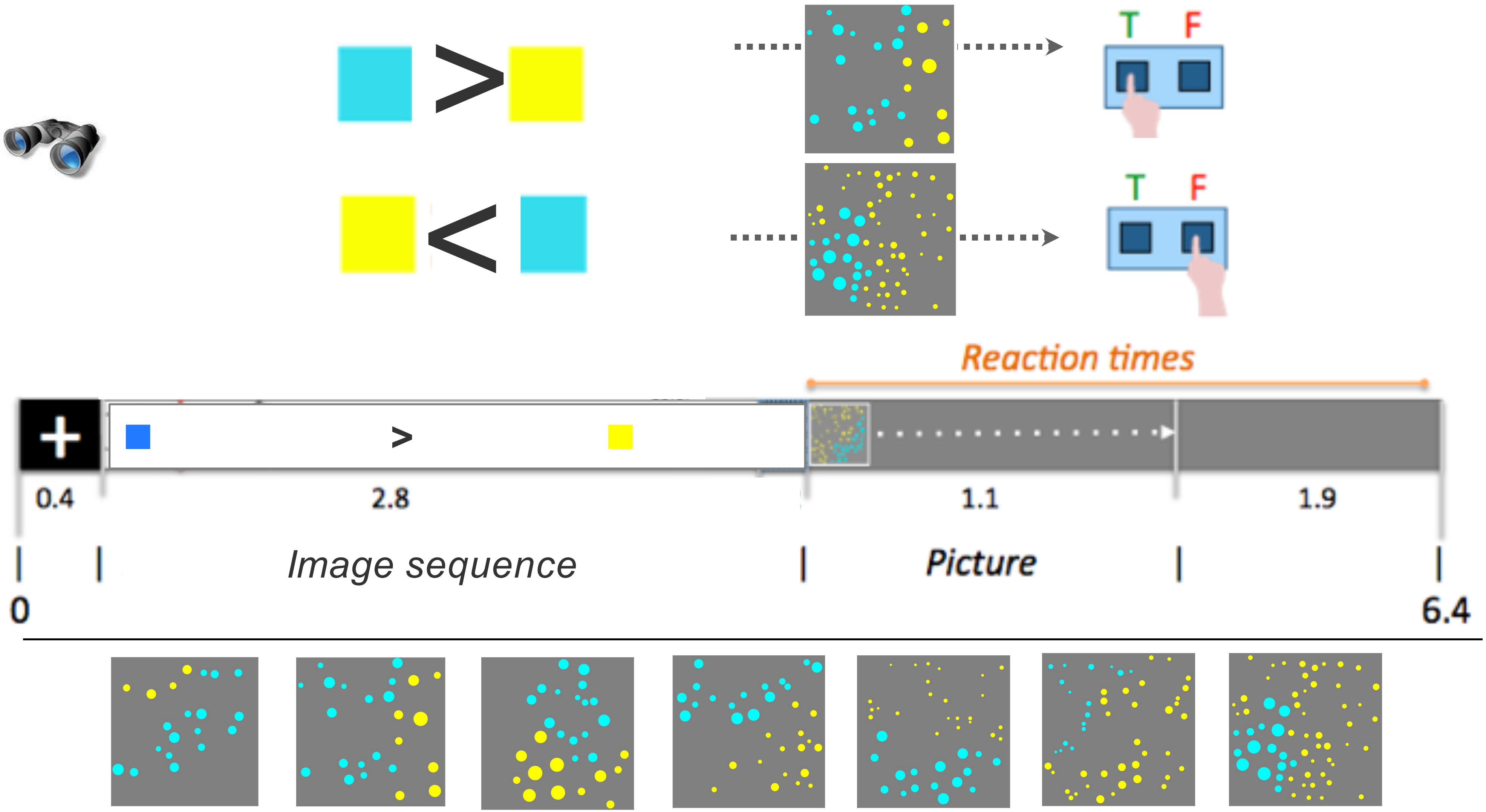






A non-verbal PPP: verification with symbols

"Your task is to determine whether the instruction matches the scenario in the image, and do so as quickly as you can"



Factors in this design

- Expression type

Non-linguistic:

< >

Linguistic: ***Q of the circles are blue***

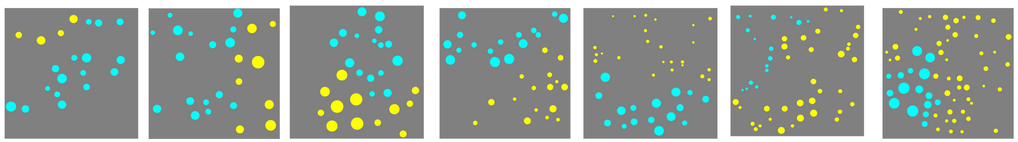
- Quantifier Type and Monotonicity

Fixed standard
POS: ***More-than-half of the circles are blue***
NEG: ***Less-than-half of the circles are yellow***

Degree
POS: ***Many of the circles are blue***
NEG: ***Few of the circles are yellow***

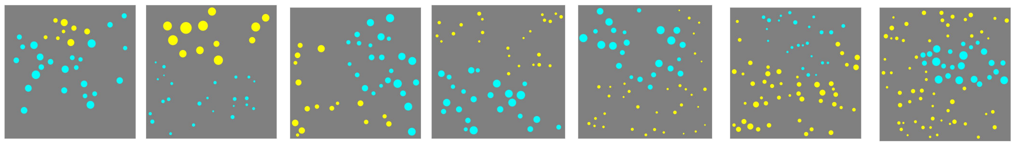
- Proportion and Numerosity

r=16



4:16 8:16 12:16 16:16 24:16 34:16 46:16

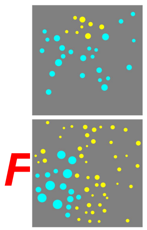
r=24



8:24 12:24 16:24 24:24 34:24 46:24 58:24

- Truth-value

More-than-half of the circles are blue



T
F

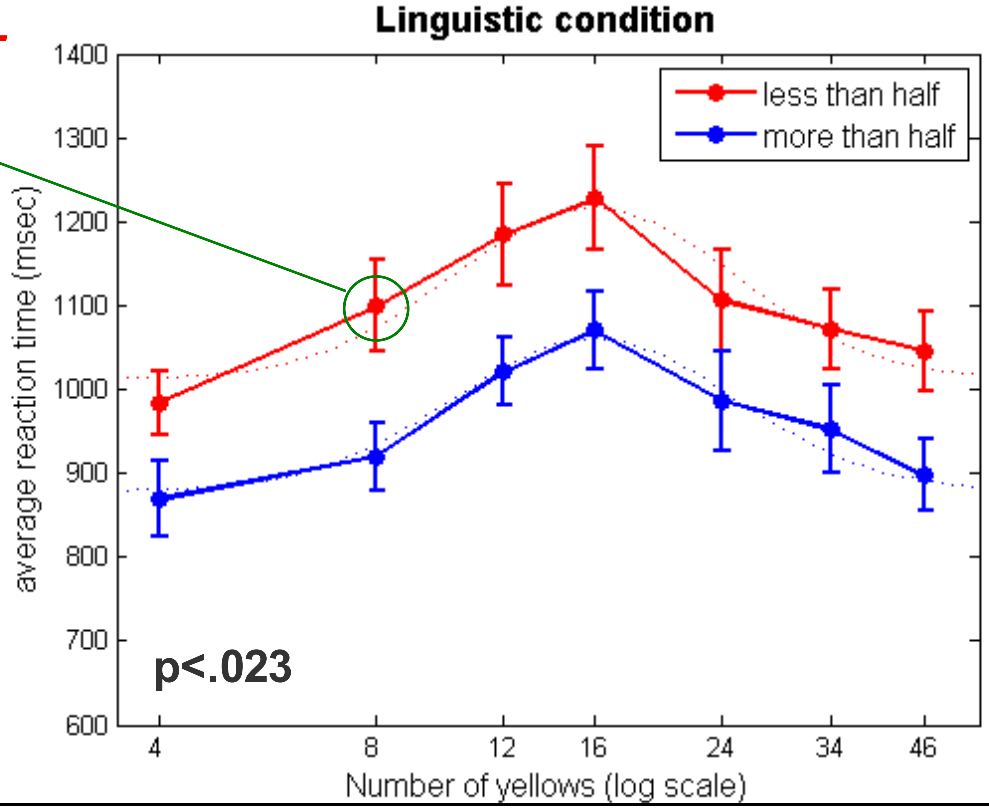
First PPP result: Polarity matters – RT functions

Less than half of the circles are blue

More than half of the circles are blue

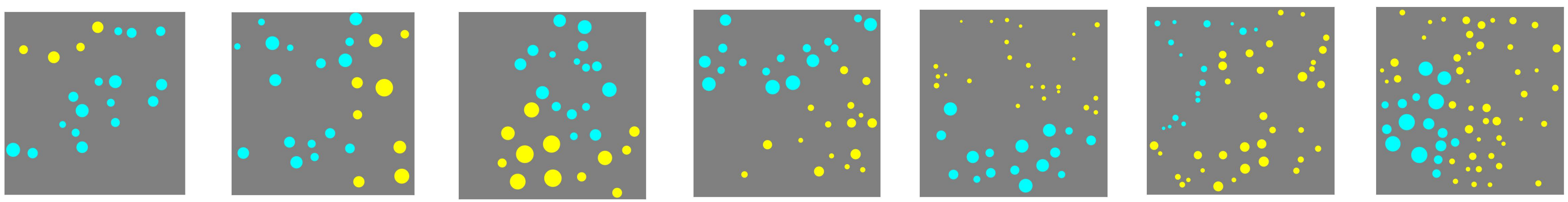
Splitting the previous graph: 17 subjects *X* 2 quantifiers *X* 16 T/F =272 trials

RT



NB: same results for *r*=24, and for the *many*/*few* contrast

#yellow/16 Blue

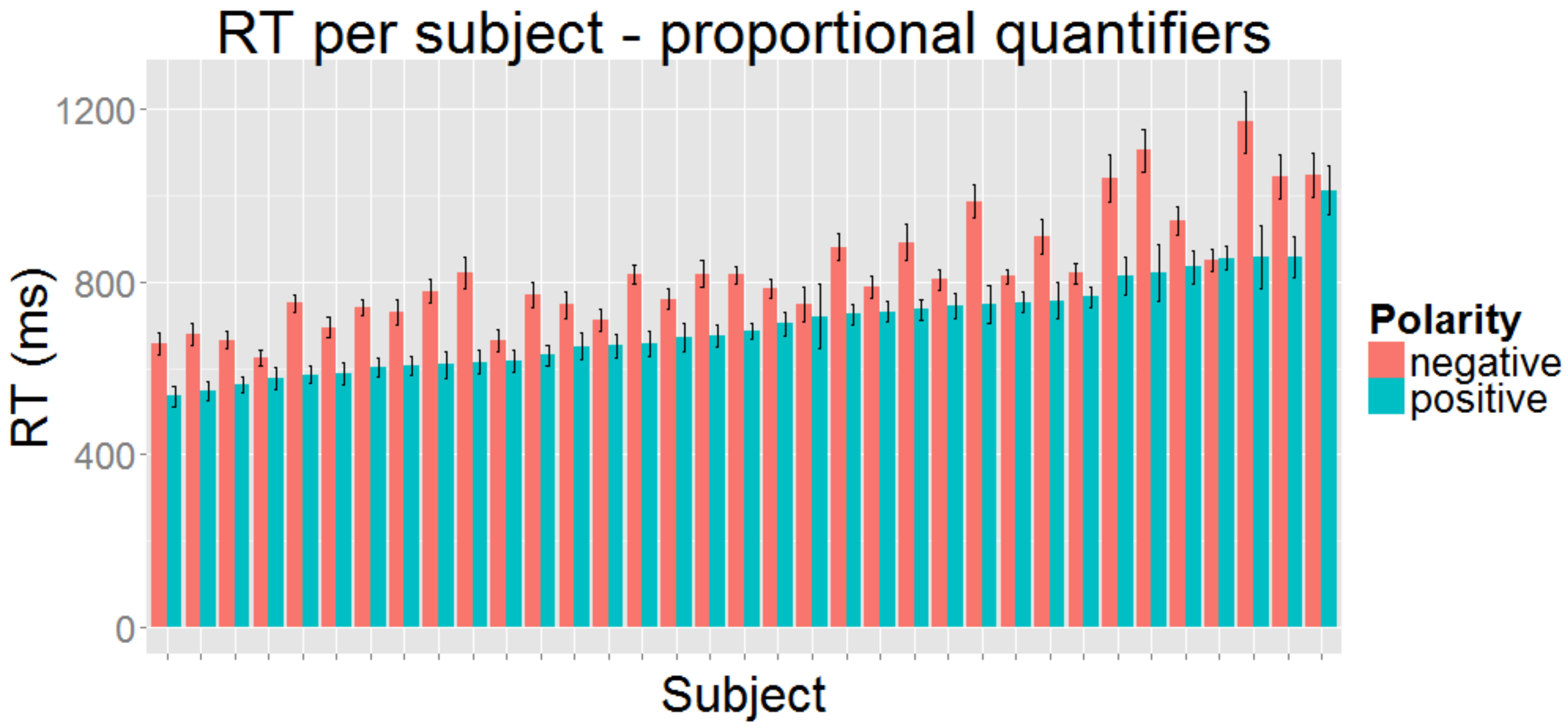


See also: Cummins & Katsos, *Cognition*, 2010

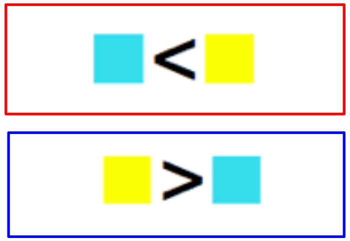
Second PPP result: Polarity difference even at the individual subject level!

Less-than-half of the circles are blue

More-than-half of the circles are blue

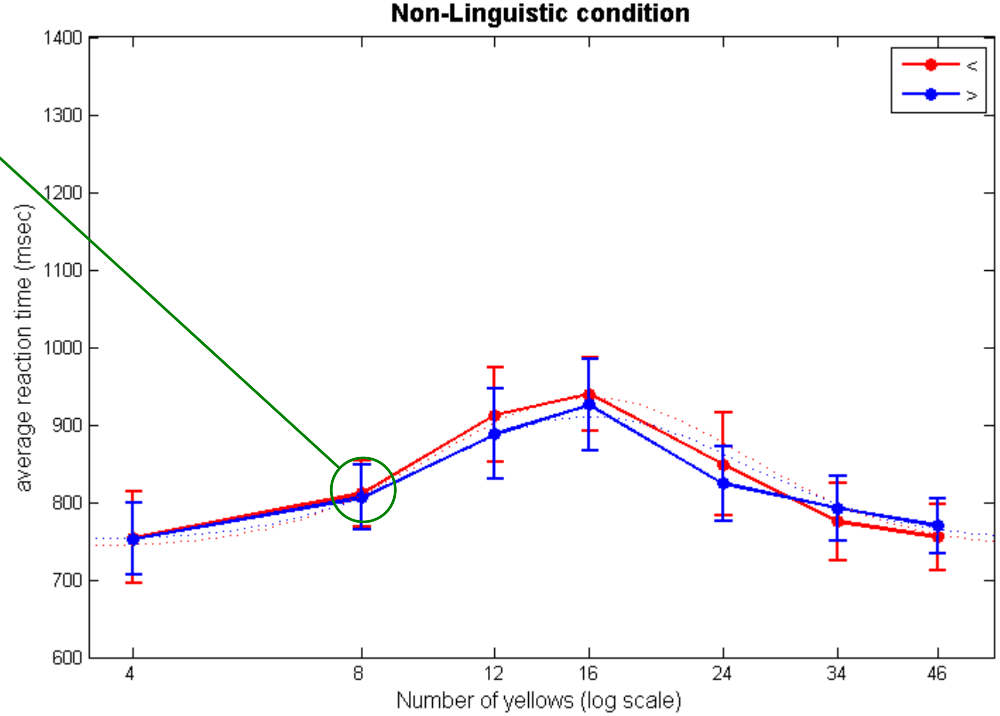


Third PPP result: verification with analogous symbols



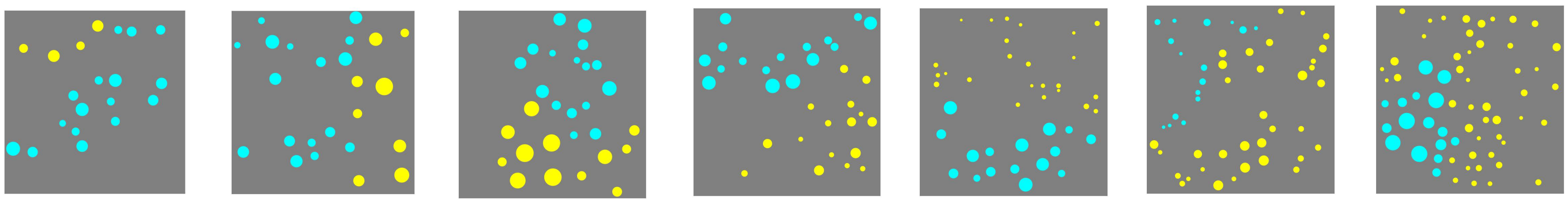
272 trials

RT

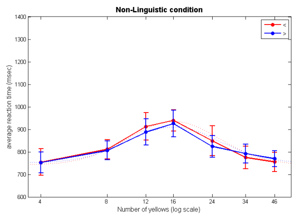


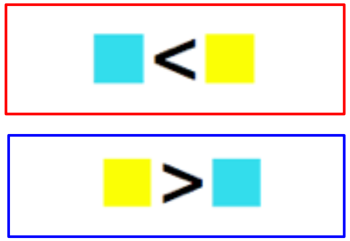
NB: same results for *r*=24

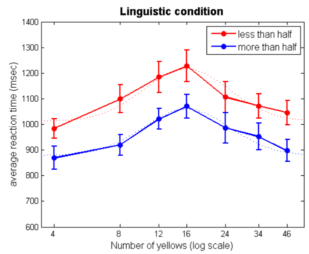
#yellow/16 Blue



Fourth PPP result: Polarity X ±linguistic interaction

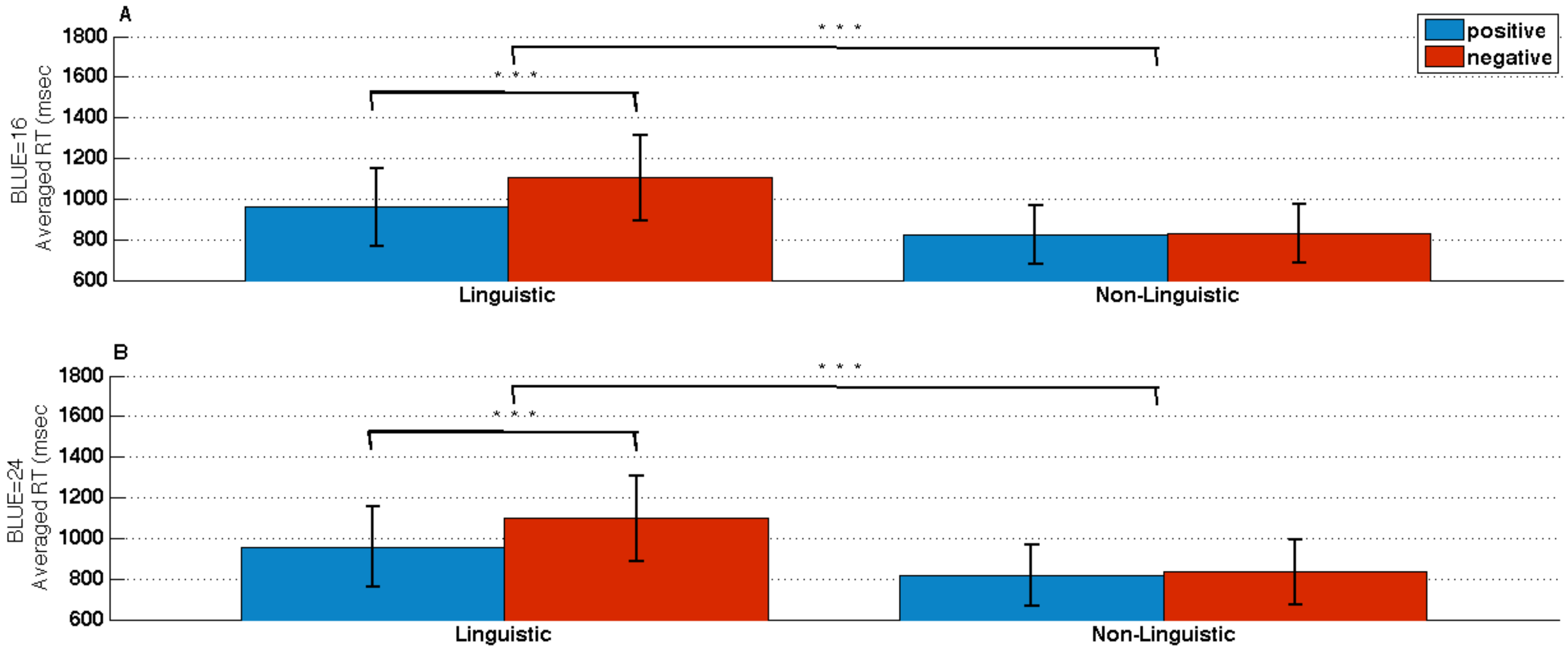






Less than half of the circles are blue

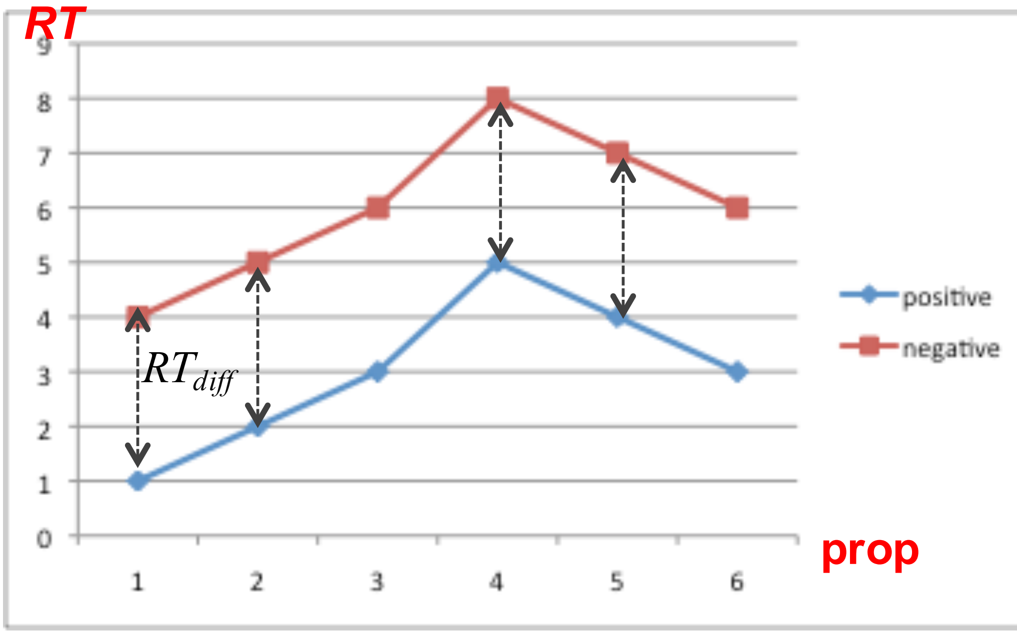
More than half of the circles are blue



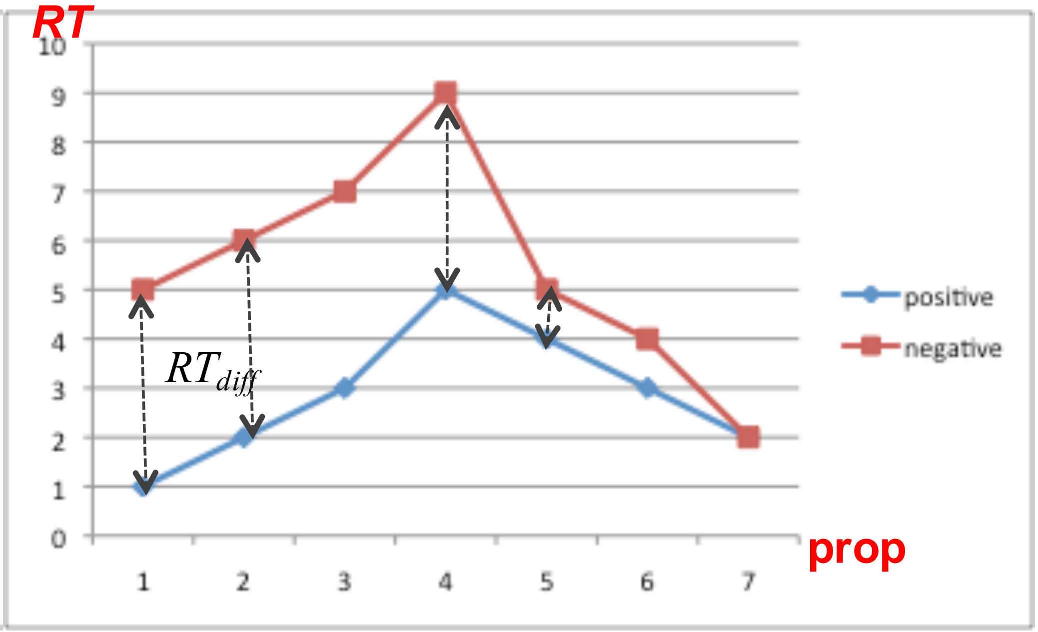
Fifth PPP result: the Polarity effect is additive

Possible relations between curves

Additive: Polarity effect is independent from proportion



Non-additive: Polarity effect is *not* independent from proportion

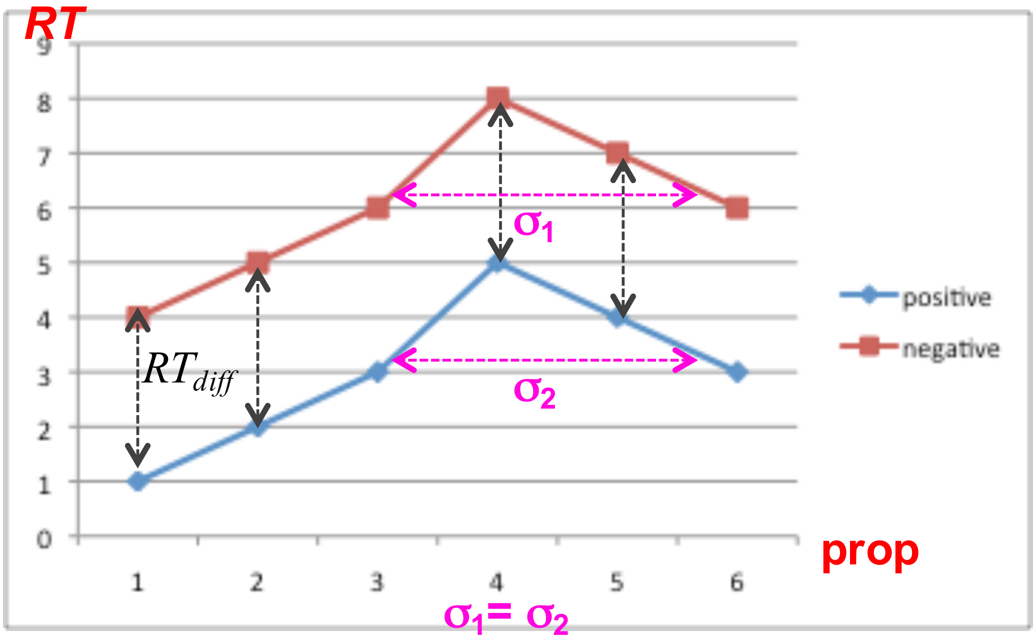


Permutation tests indicate that the effect is additive. RT_{diff} is independent of r/c.

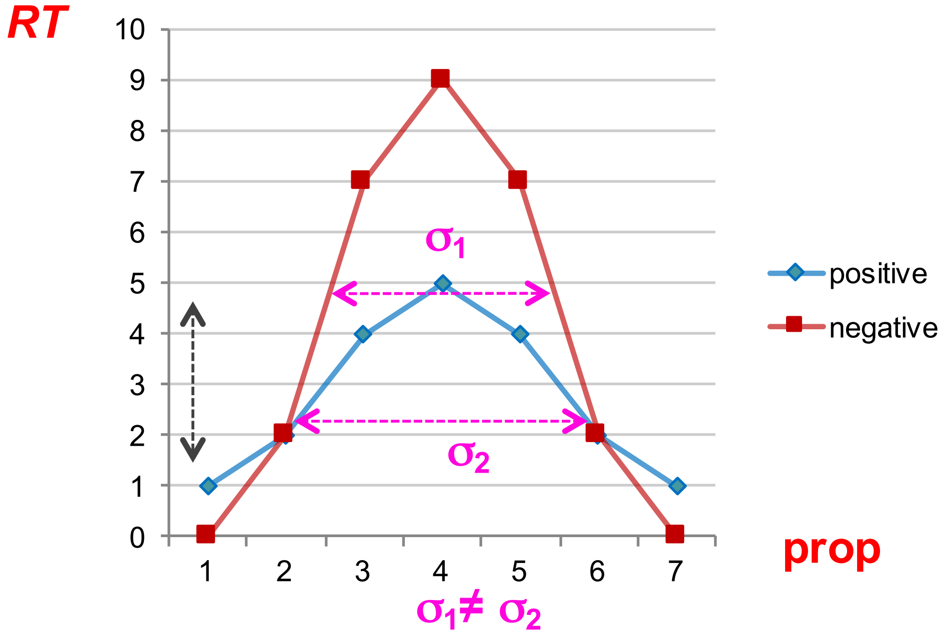
Fifth PPP result: the Polarity effect is additive

Possible relations between curves

<u>Additive</u>: Polarity effect is independent from proportion



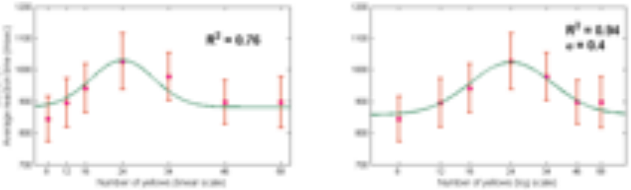
<u>Non-additive</u>: Polarity effect is *not* independent from proportion

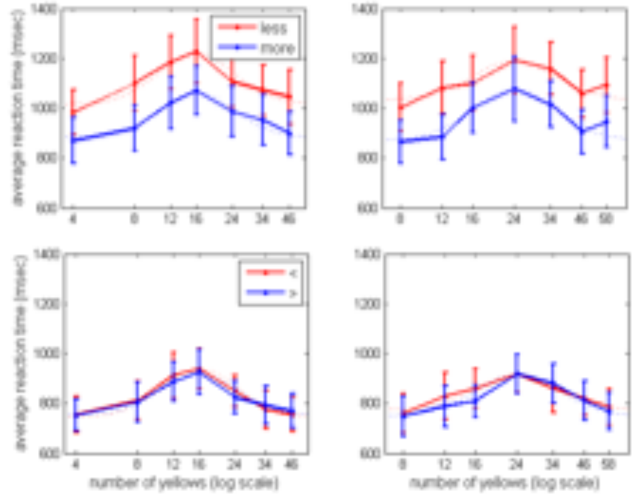


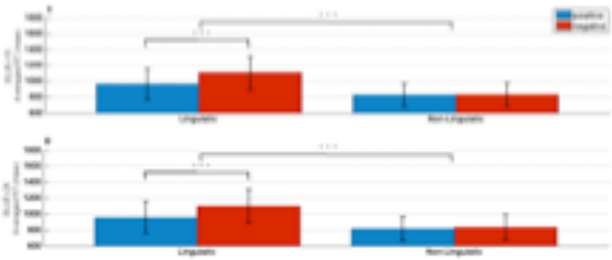
Permutation tests indicate that the effect is additive. RT_{diff} is independent of r/c.

$\Rightarrow$ *Verification is unaffected by proportion; contrary to the focus-on-the-larger set strategy*

Results and conclusions so far







- *Weber's Law*: Performance curves on the PPP is more symmetric on logarithmic compression

- *Quantifier Polarity*:

  $RT_{few,\ less\text{-}than\text{-}half} > RT_{many,\ more\text{-}than\text{-}half}$

- *No symbolic Polarity*: $RT_{<} \approx RT_{>}$

- *Modularity I*: Polarity effects are exclusive to Language: a Polarity X instruction type (±linguistic) interaction effect

- *Modularity II*: the Polarity effect is additive (RT_{diff} is independent of proportion)

What we did last time

- The localizationist agenda: pieces of language in brain pieces.

  - underscores the need for precise definitions of the language pieces and the brain pieces.

  - our pieces so far are semantic: pieces of semantic knowledge for which a clear brain basis is likely to be identified.

- Polarity: certain quantifiers appear to have antonyms:

  - <few, many>, <more-than-half, less-than-half>

  - these pairs contrast in important ways:

- Polar quantifiers behave as if one of them contains a negation. Evidence:

  - NPI licensing

  - entailment reversal

  - processing costs

*Arguments for J&C's view on negation in **few**:* *negative quantifiers behave as it they contain a covert negation*

Negation-containing operators license Negative Polarity Items

(2) a. ***All** of the students *ever*$_{NPI}$ climbed Mount Everest

b. **None** of the students *ever*$_{NPI}$ climbed Mount Everest

Quantifiers of degree and proportion replicate this pattern

(3) a. ***Many** of the students *ever*$_{NPI}$ climbed Mount Everest

b. **Few** of the students *ever*$_{NPI}$ climbed Mount Everest

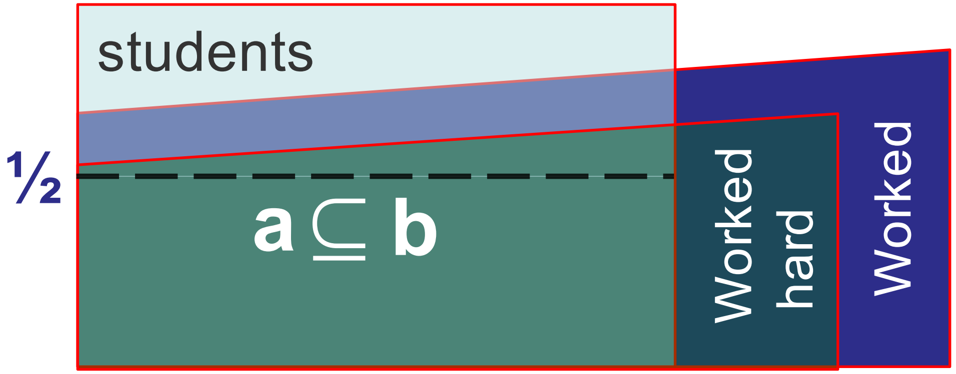
(4) a. **All** of the students worked hard $\Rightarrow$ **All** of the students worked

b. **None** of the students worked $\Rightarrow$ **None** of the students worked hard

More: negative quantifiers reverse entailment patterns

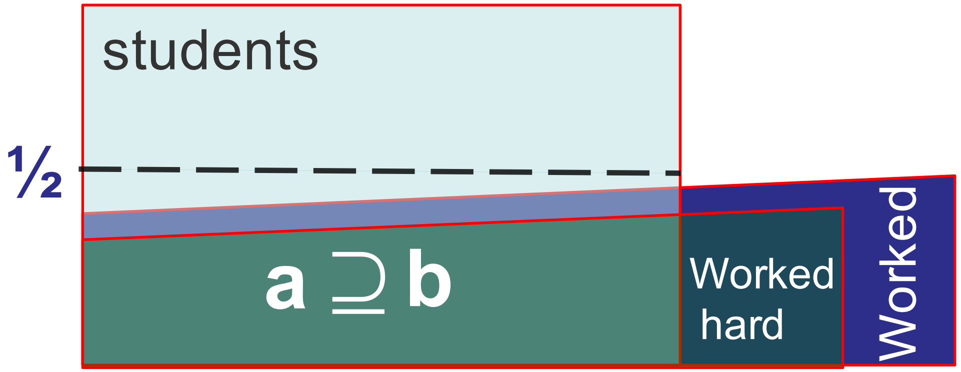
(5) *Positive quantifiers – from subsets to supersets (Monotone-↑):*

a. **>½** of the students worked hard ⇒ b. **>½** of the students worked



(6) *Negative quantifiers – from supersets to subsets (Monotone-↓):*

a. **<½** of the students worked hard ⇐ b. **<½** of the students worked

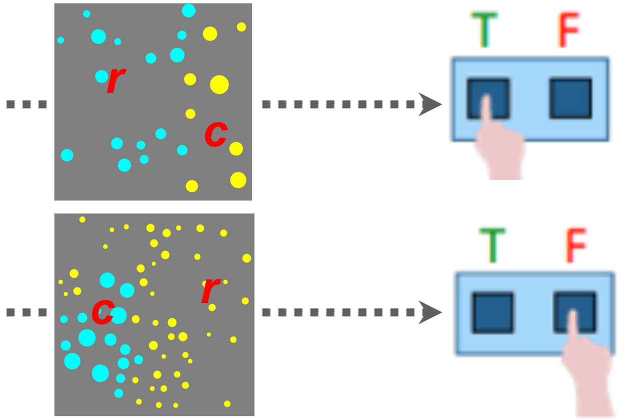


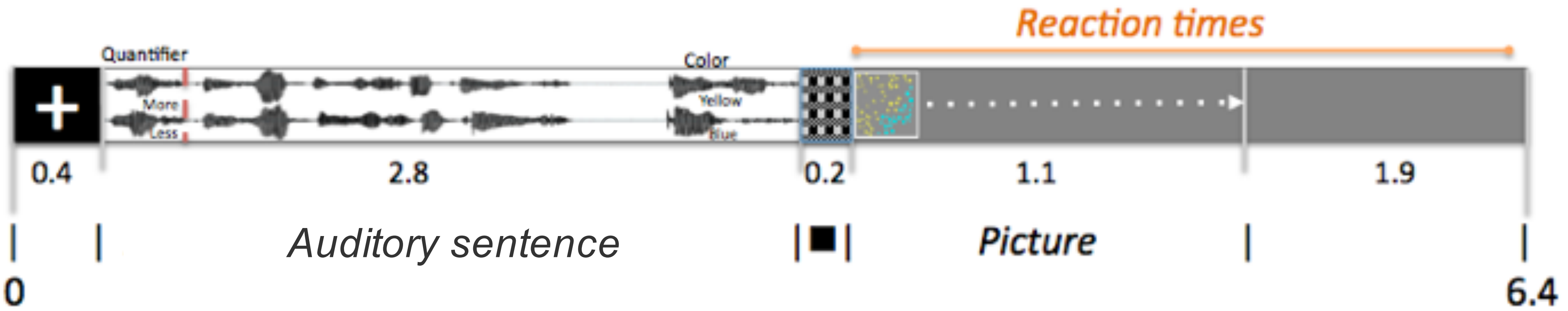
An RT experiment with the Parametric Proportion Paradigm (PPP)

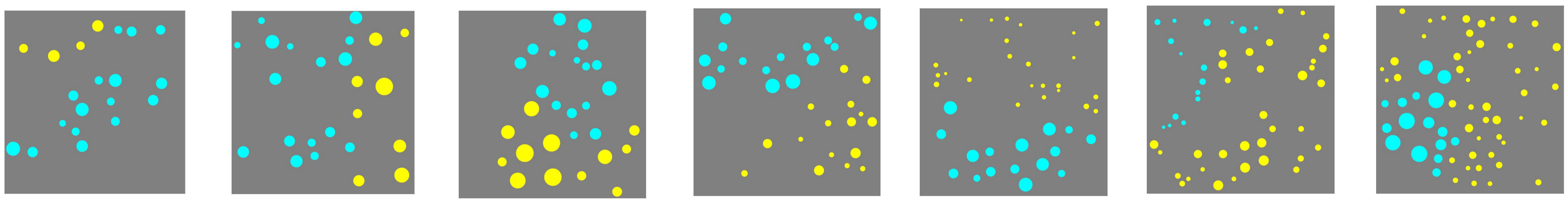
(with Isabelle Deschamps, McGill. Galit Agmon & Yonatan Loewenstein, HUJI)

POS:
More-than-half of the circles are blue

NEG:
Less-than-half of the circles are yellow

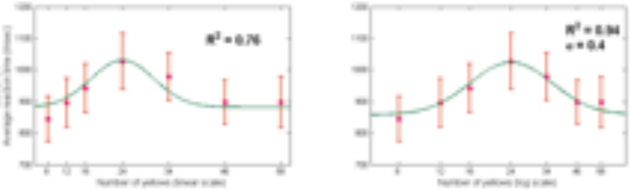






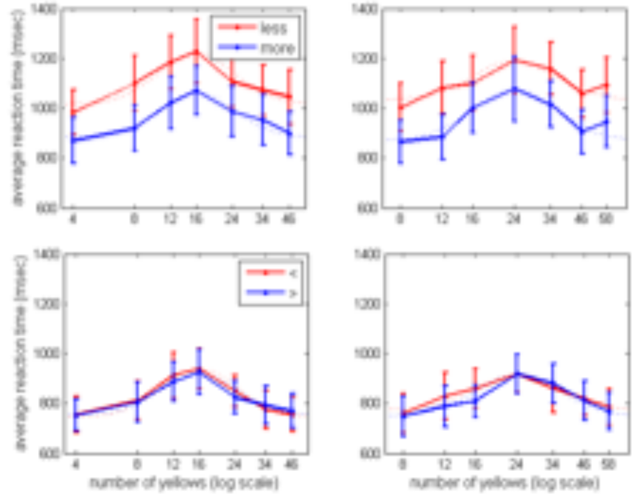
Results and conclusions so far

- *Weber's Law*: Performance curves on the PPP is more symmetric on logarithmic compression



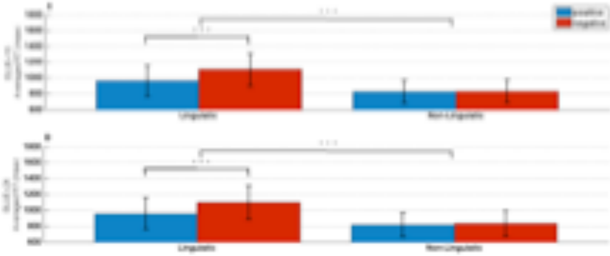
- *Quantifier Polarity*:

  $RT_{\textit{few, less-than-half}} > RT_{\textit{many, more-than-half}}$



- *No symbolic Polarity*: $RT_{<} \approx RT_{>}$

- *Modularity I*: Polarity effects are exclusive to Language: a Polarity X instruction type (±linguistic) interaction effect



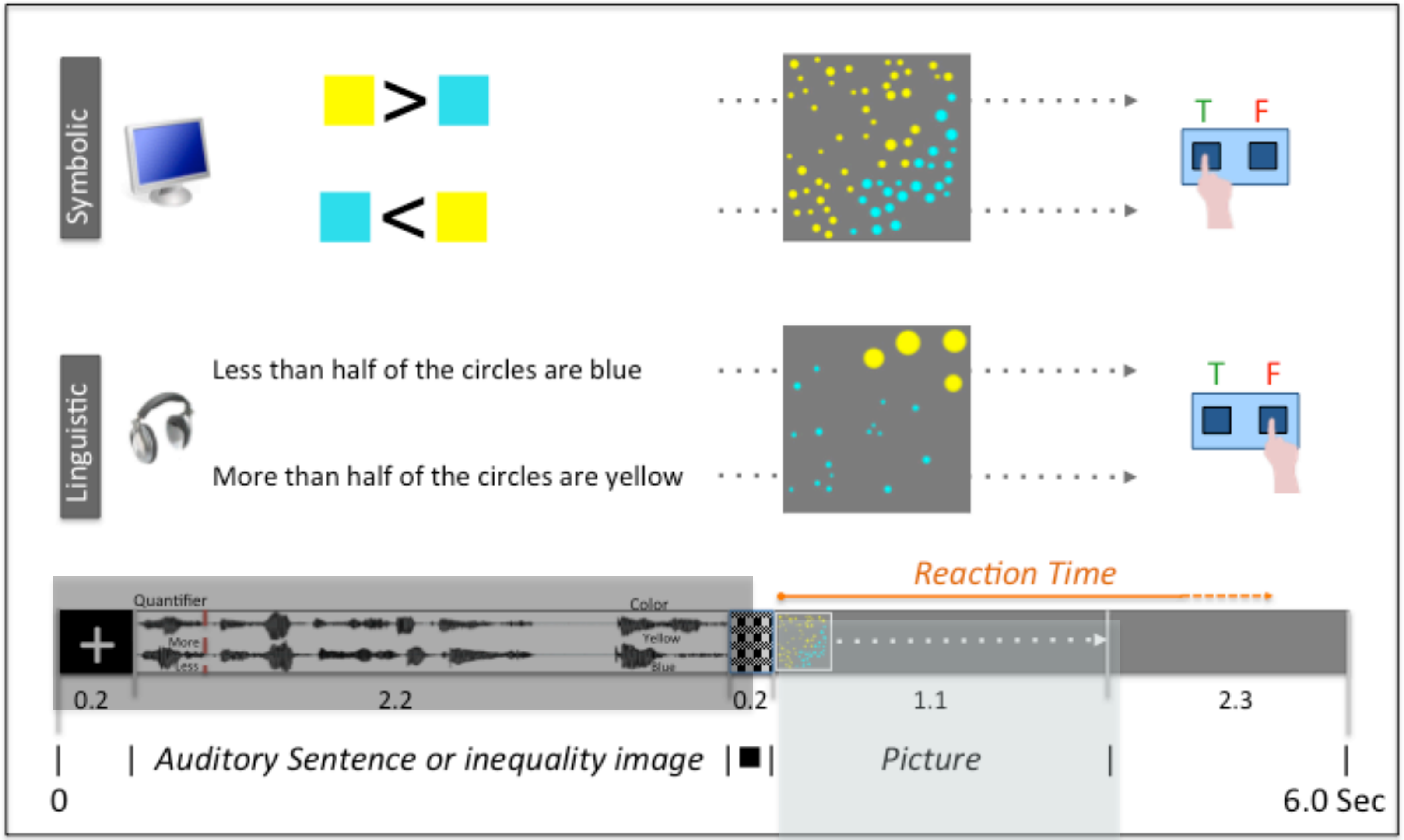
- *Modularity II*: the Polarity effect is additive (RT_{diff} is independent of proportion)

today's menu

- Quantifier polarity and the localizationist agenda
  - an fMRI experiment with quantifiers: the brain location of polarity
  - a similar experiment with brain-damaged individuals with aphasia
- Comparatives: data and problems
  - an RT experiment with comparatives
  - a polarity problem with comparatives
- Solution?
  - monotonicity vs. negation (Ladusaw, 1979)
  - the monotonicity of comparatives
  - processing costs of monotonicity

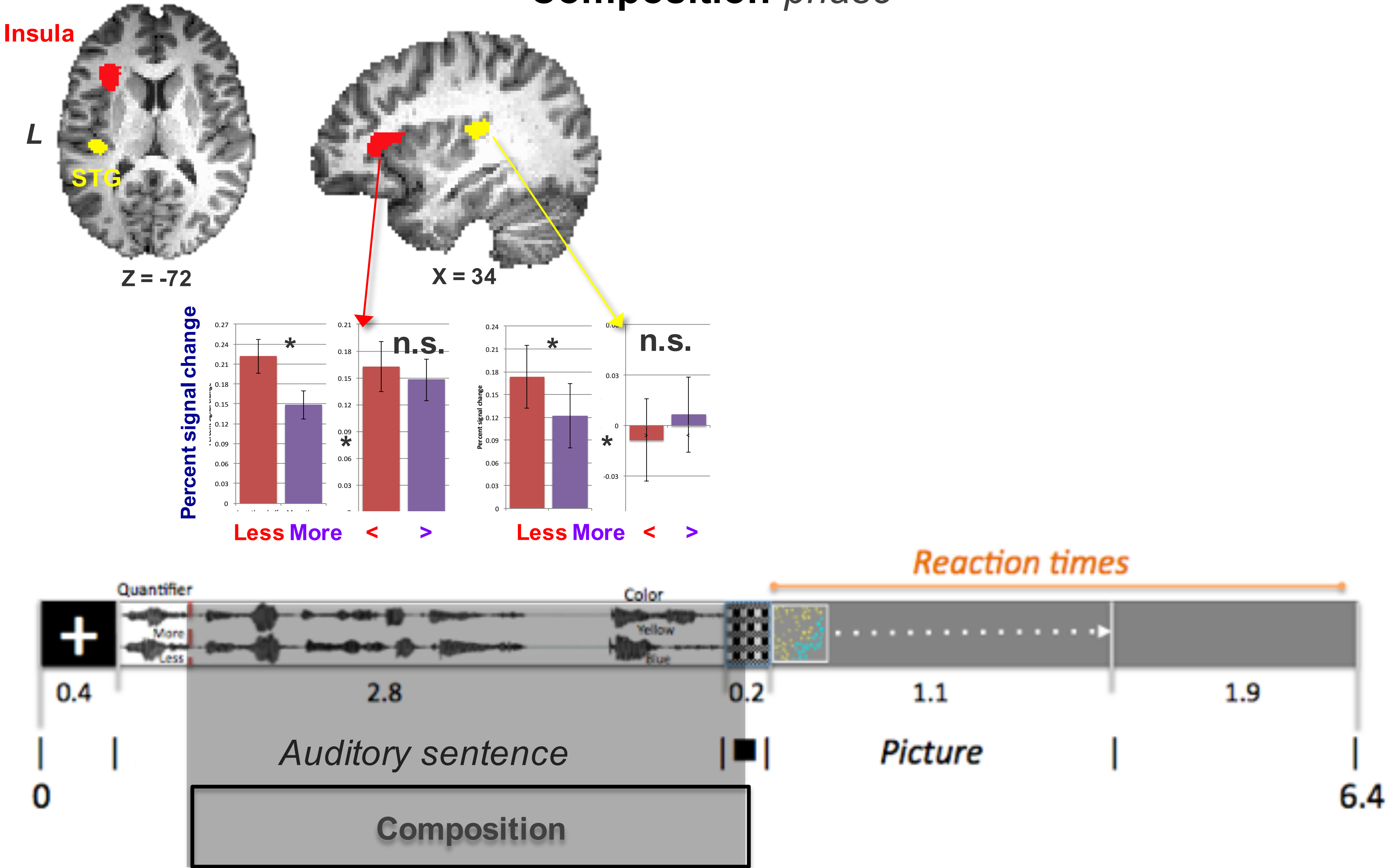
fMRI experiment

(with Isabelle Deschamps, McGill, Galit Agmon & Yonatan Loewenstein, HUJI)

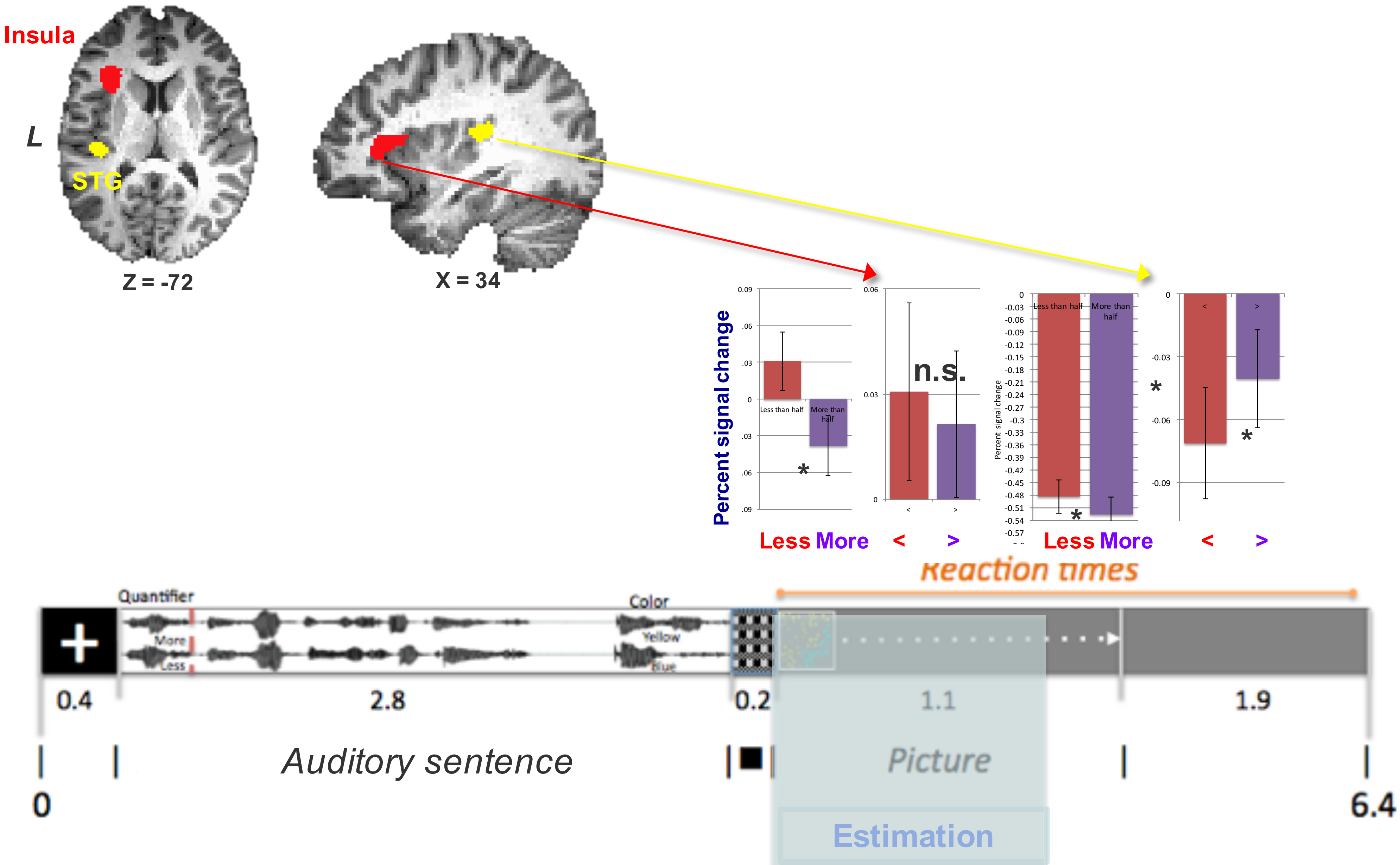


Composition | **Estimation** **Comparison**

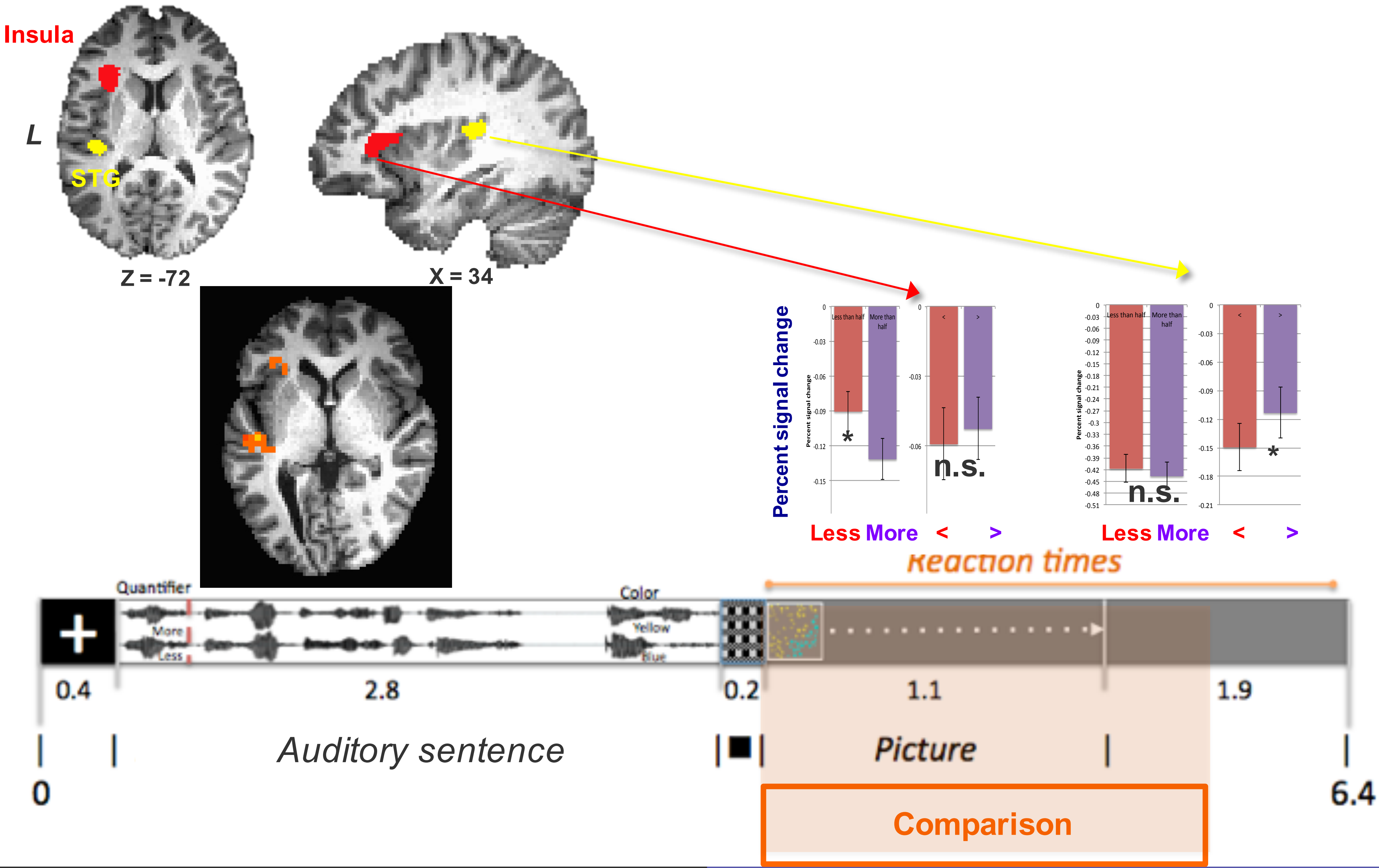
Regions in which we find ***Instructions X Polarity*** *Interaction during the* **Composition** *phase*



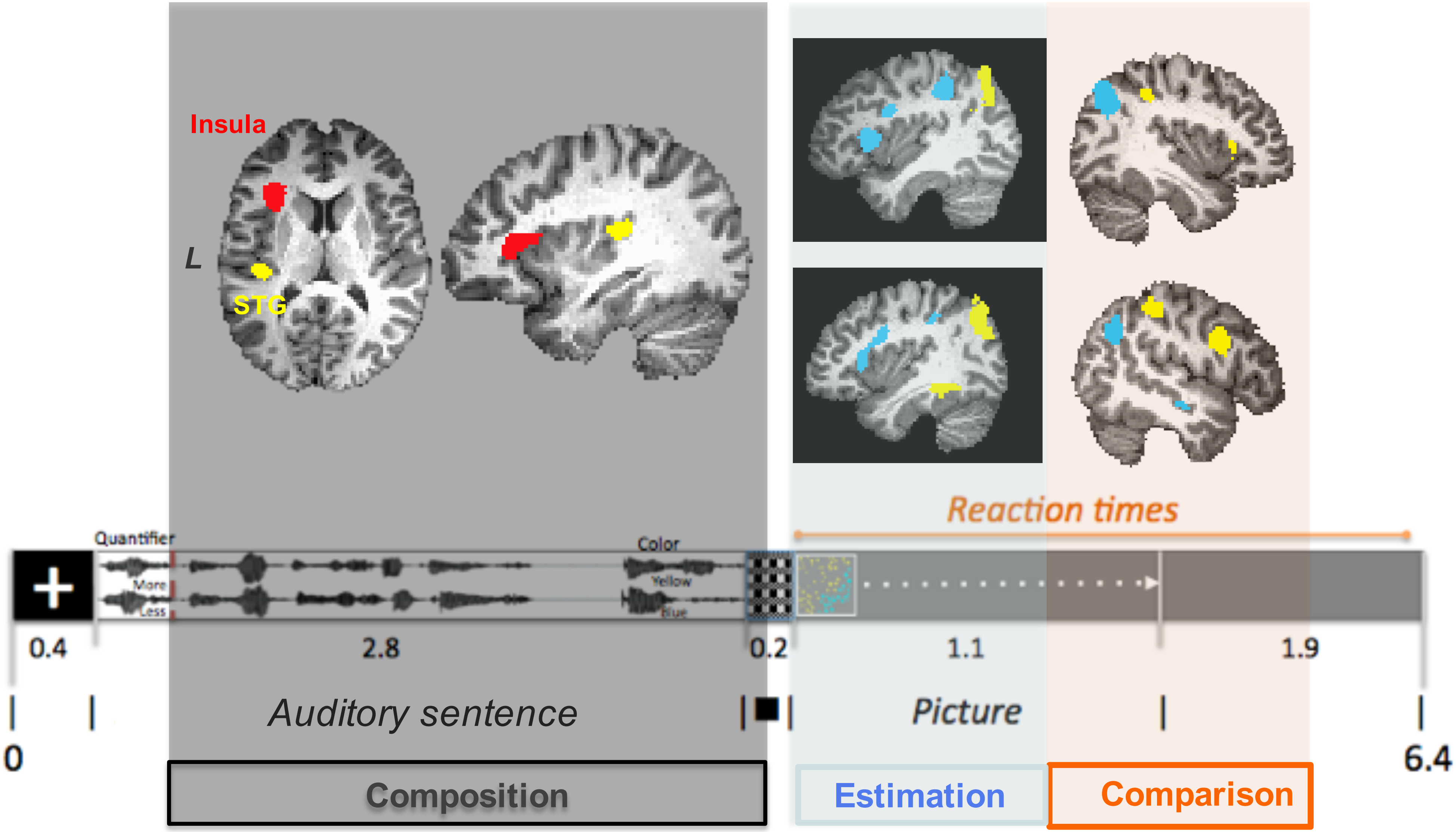
Same regions, **Estimation** *phase*



Same regions, **Comparison** *phase*

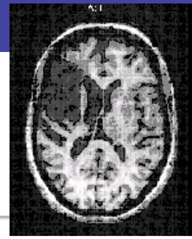


*Strict Neural Modularity - **no** Language/math interactions:*



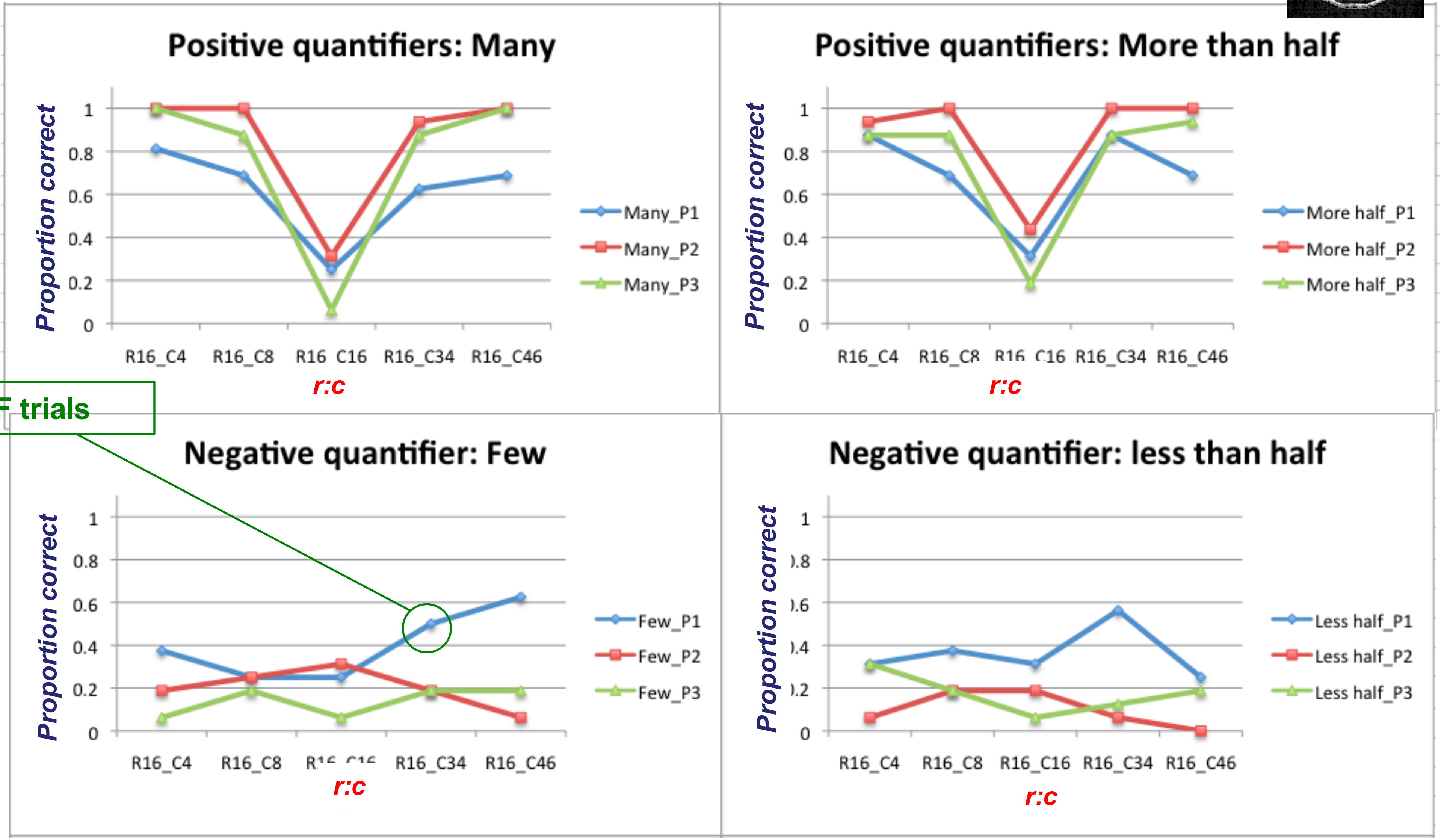
no* Estimation/Comparison *effects
in* Composition *phase

no* Composition *effects
in* Estimation/Comparison *phase

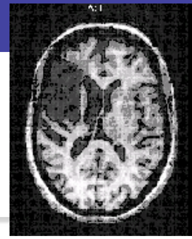


The PPP in Broca's aphasia
(with Virginia Jaichenco, Martin Fuchs, UBA, Isabelle Deschamps, Laval)

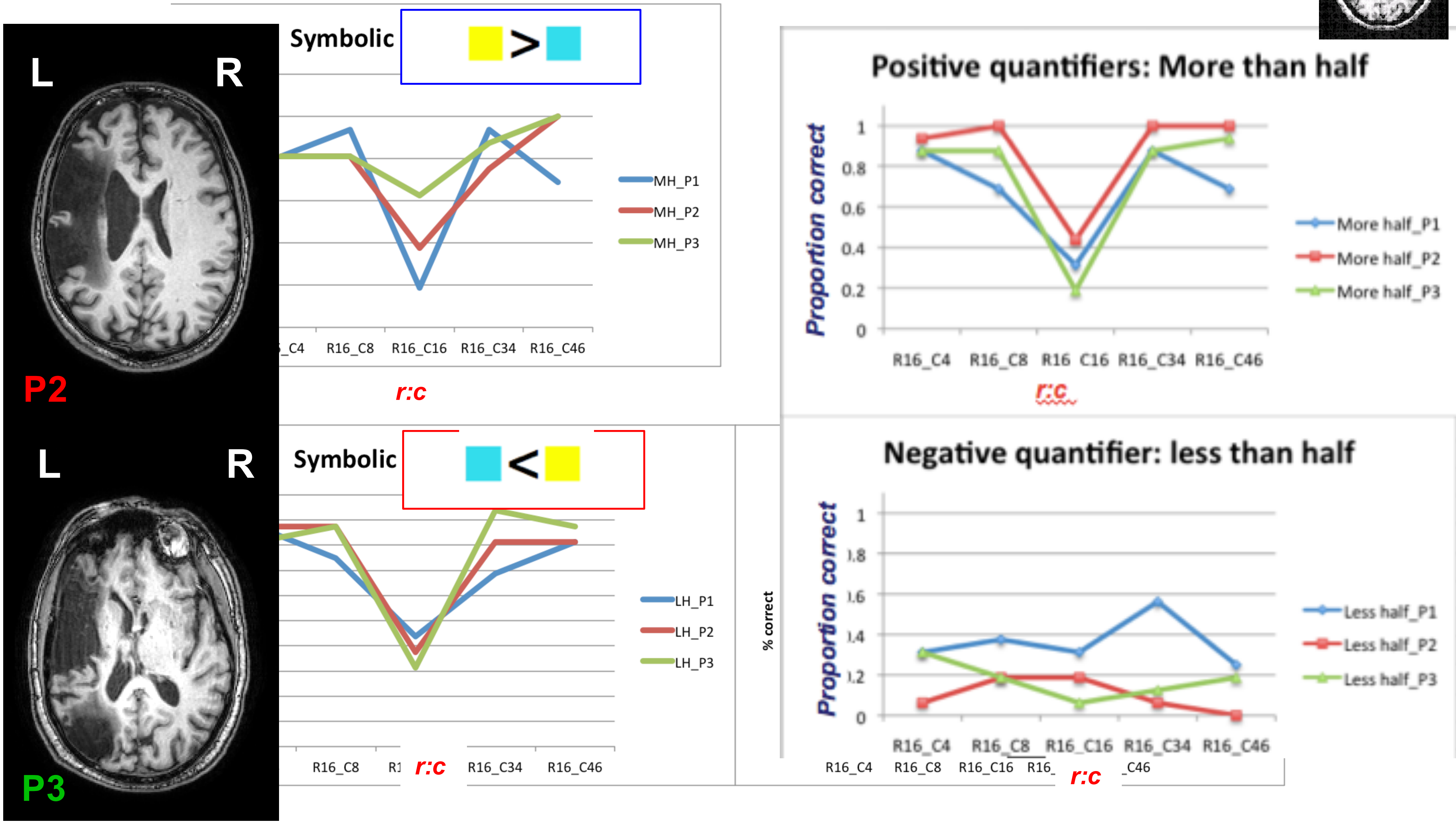
16 T/F trials



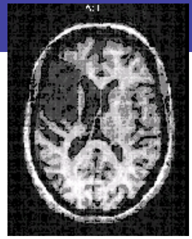
Individual patients' error pattern subsequent to a lesion in Broca's region



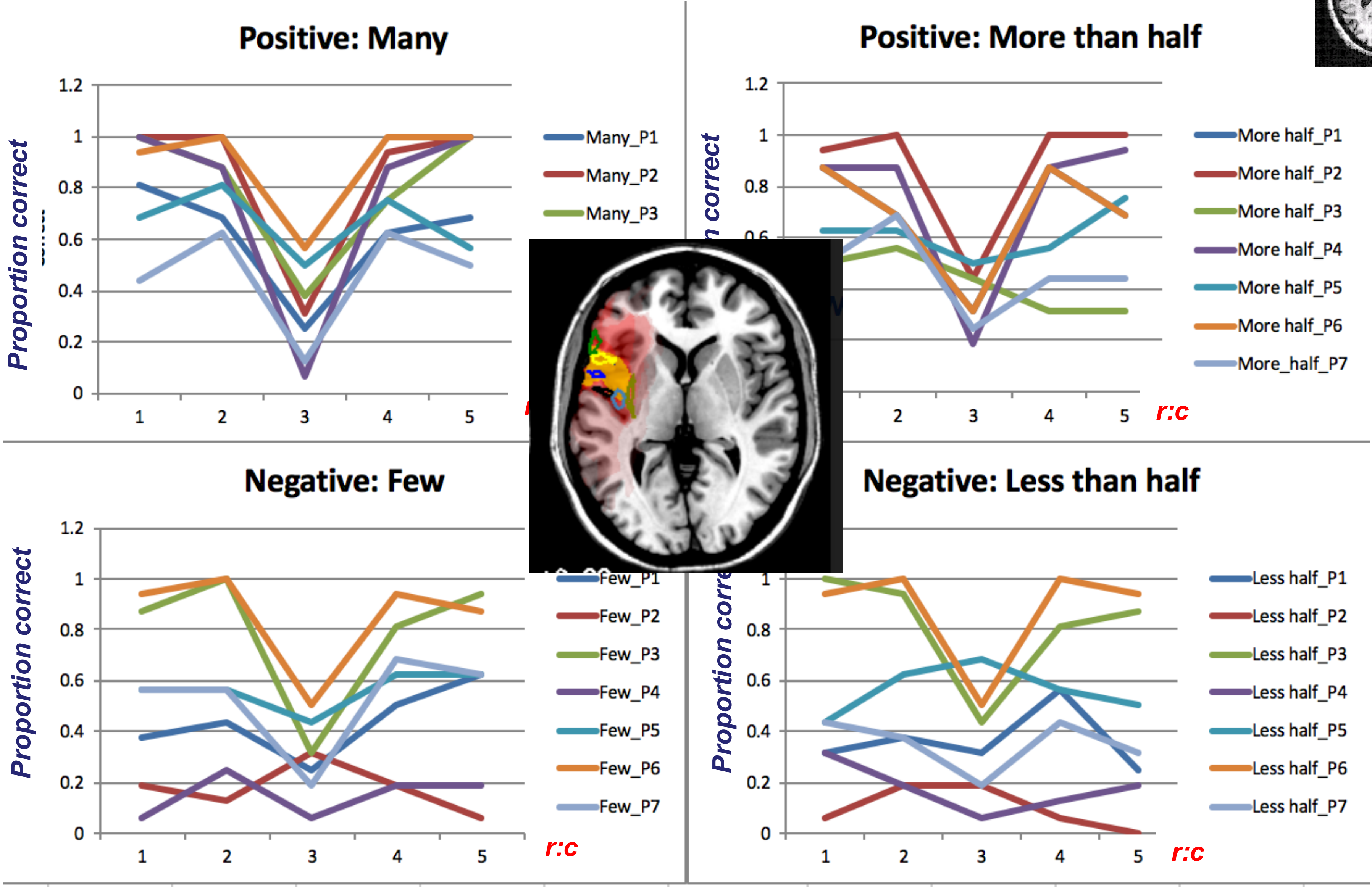
The PPP in Broca's aphasia



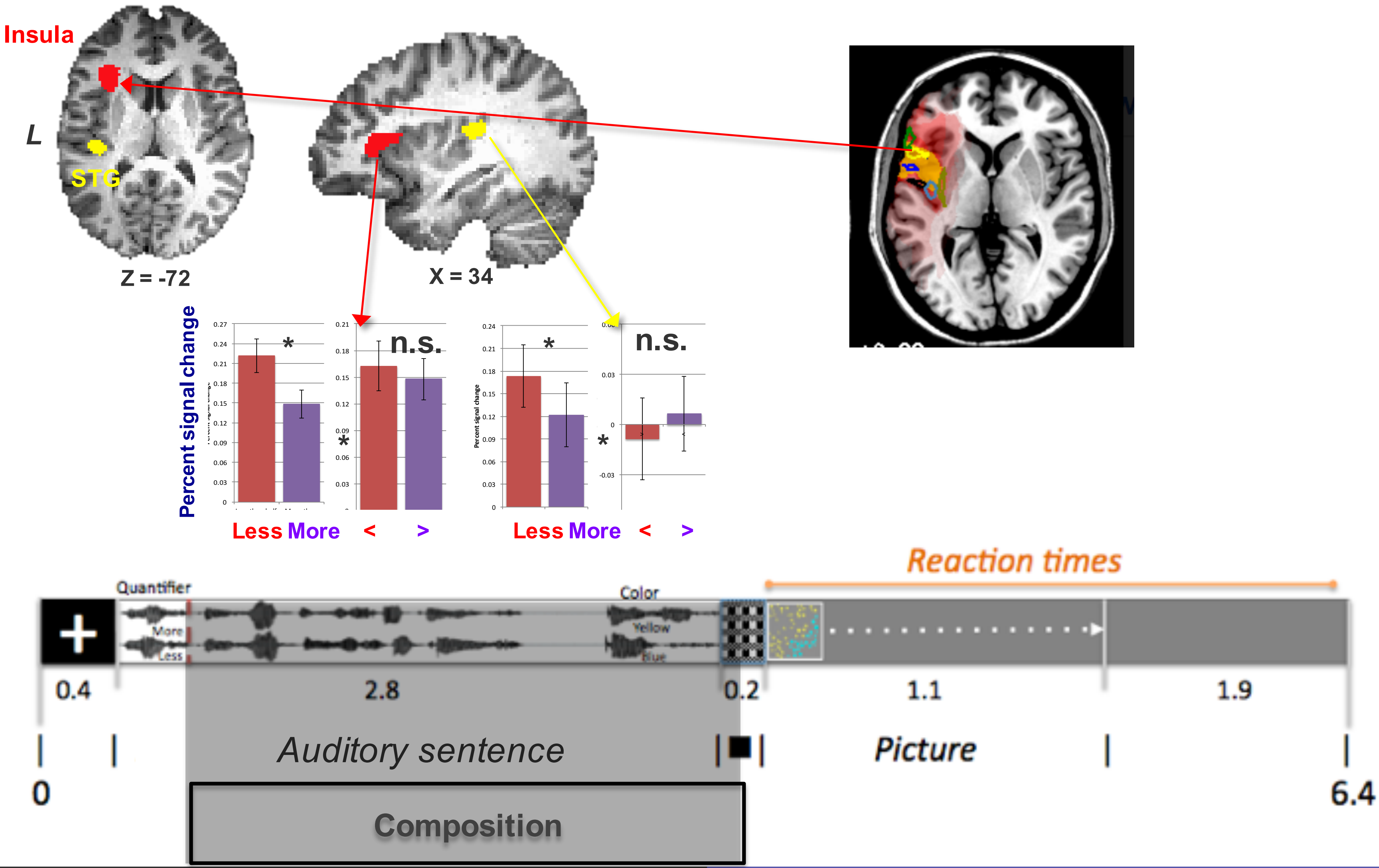
Individual patients' error pattern subsequent to a lesion in Broca's region



The PPP in Broca's aphasia

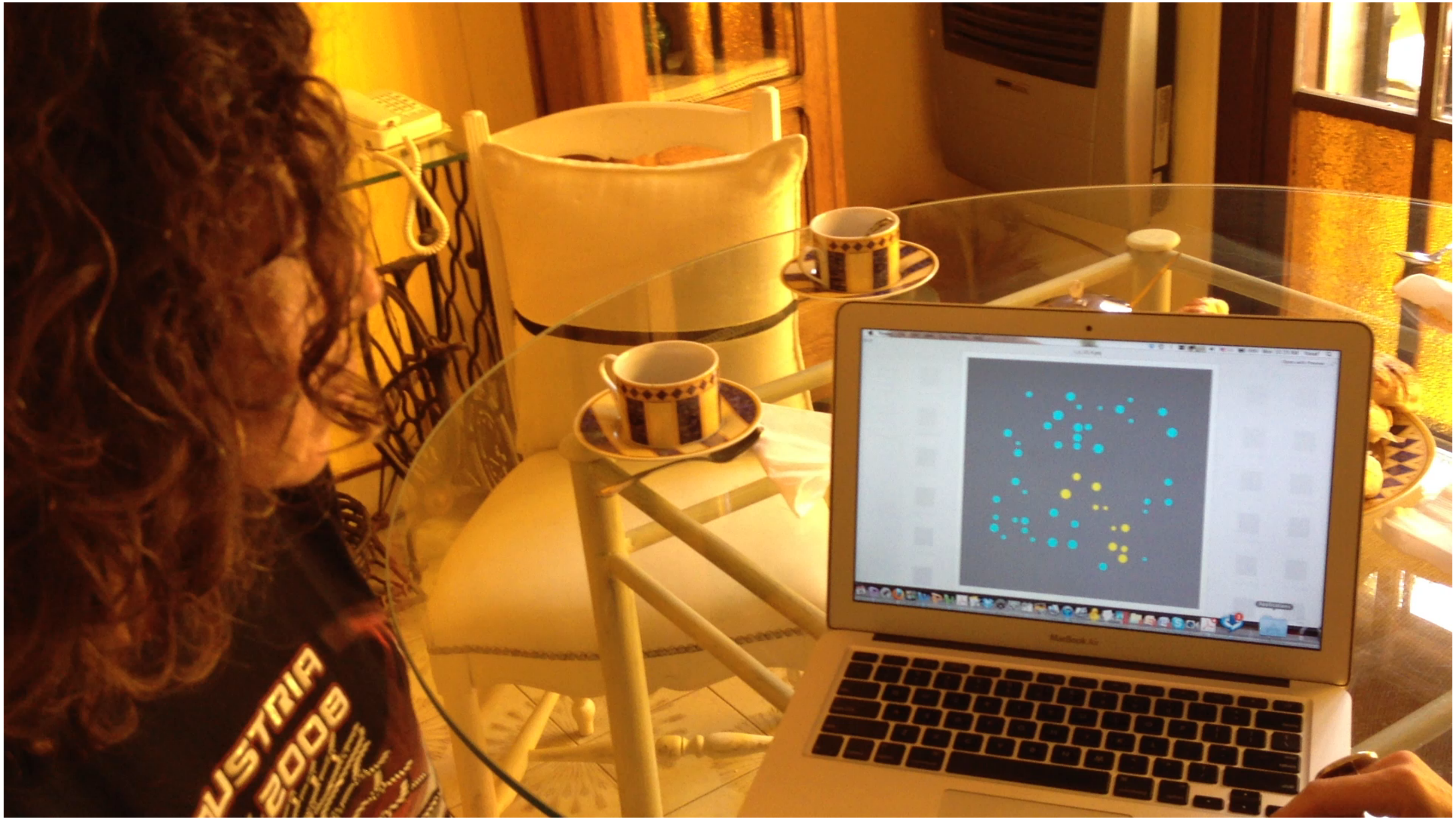


Individual patients' error pattern subsequent to a lesion in Broca's region



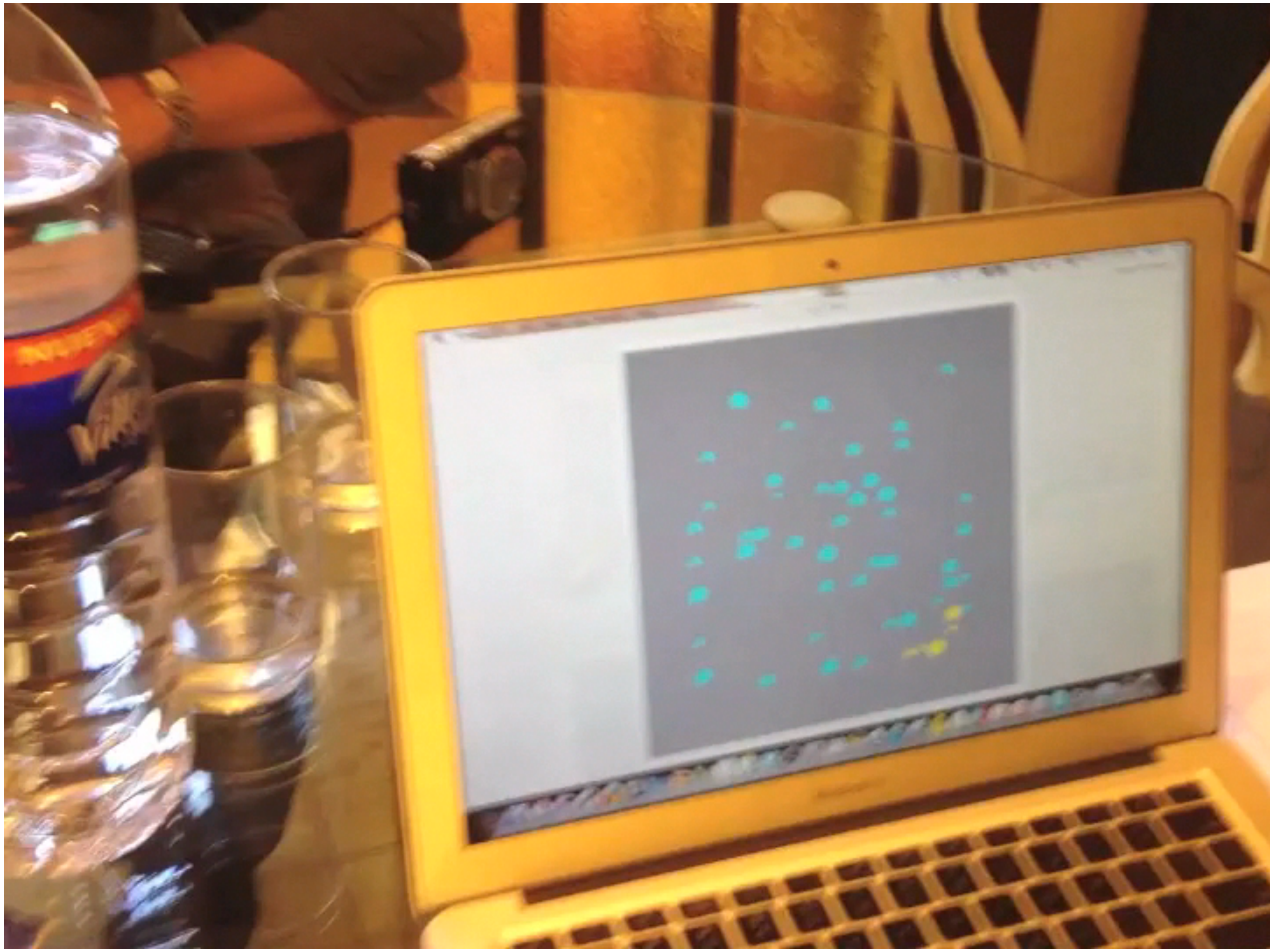
Insula
L
STG
Z = -72
X = 34
Percent signal change
*
n.s.
*
*
n.s.
*
Less More < >
Less More < >
Reaction times
Quantifier
More
Less
Color
Yellow
Blue
0.4
2.8
0.2
1.1
1.9
Auditory sentence
Picture
0
6.4
Composition

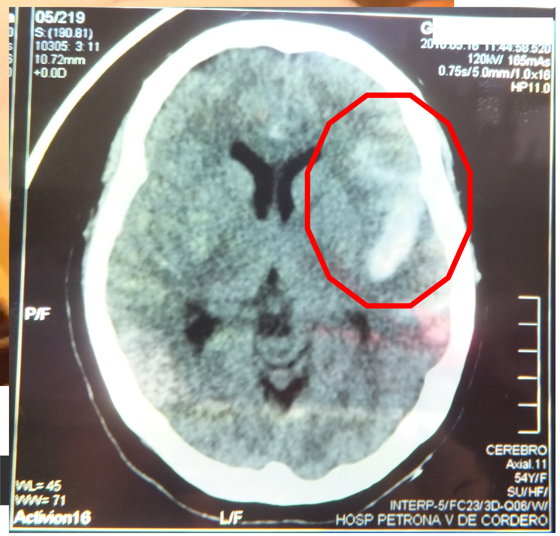
Patient demo – many (Spanish)



Many of the circles are blue ("YES")

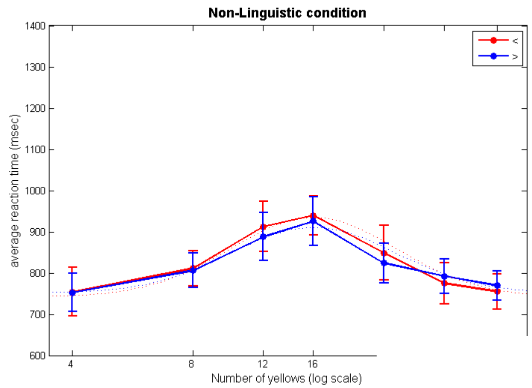
Patient demo – few (Spanish)

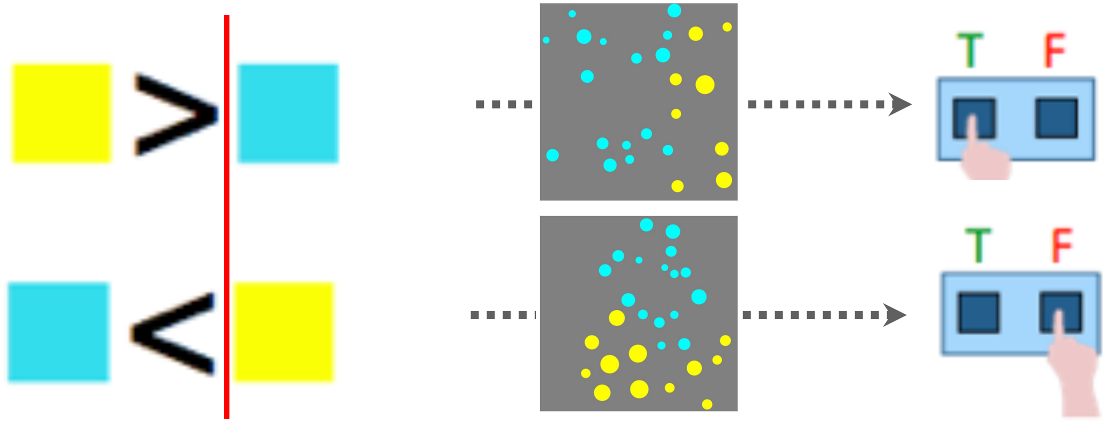


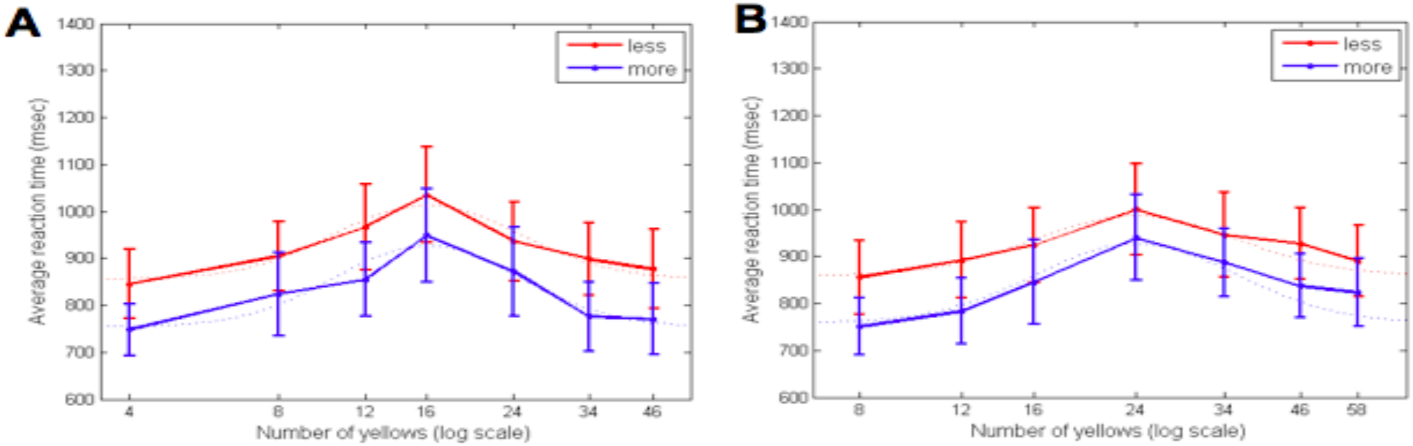


Few of the circles are blue ("

Do participants respond on partial information: a view from comparatives







Defining entailment in set theoretic terms

(7) **Sentence entailment**

- S1 entails S2, S1 ⇒ S2, if and only if every situation in which S1 holds is a situation in which S2 holds.
- {s: S1 holds in s} ⊆ {s: S2 holds in s}

(8) **VP entailment**

- VP1 entails VP2, VP1 ⇒ VP2, if and only if every individual of which VP1 holds is an individual of which VP2 holds.
- {x: VP1 holds of x} ⊆ {x: VP2 holds of x}

Ladusaw: quantifiers are either UE or DE on each argument

(9) *Definitions:*

a. a function is Upward Entailing (UE) iff for all $X \subseteq Y$, $f(X) \subseteq f(Y)$

b. a function is Downward Entailing (DE) iff for all $X \subseteq Y$, $f(Y) \subseteq f(X)$

Ladusaw: quantifiers are either UE or DE on each argument

(10) *Some – UE on both arguments*

{x: x is an olympic swimmer}⊆{x: x is a swimmer},

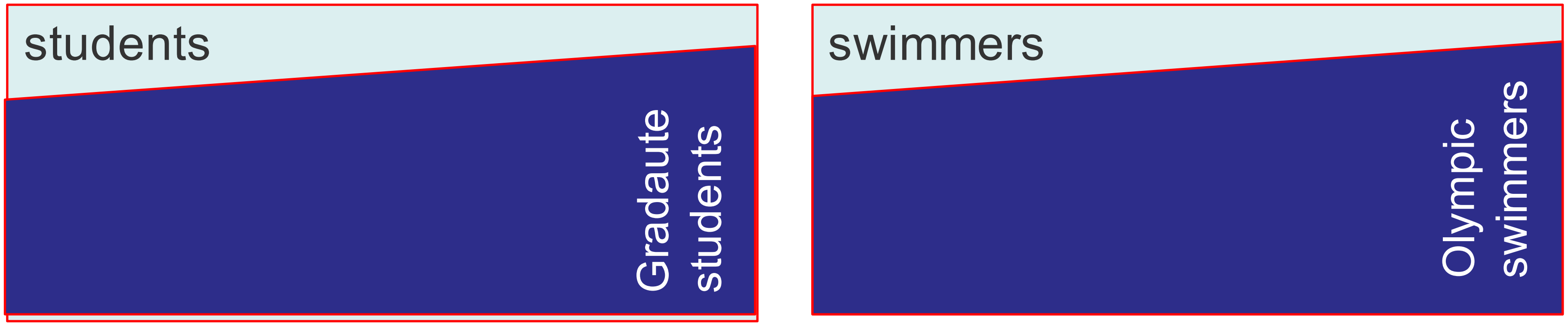
{y: y is a graduate student}⊆{y: y is a student}:

a. **Some (graduate student)** (is a swimmer) ⇒

b. **Some (student)** is a swimmer

c. **Some** student is an **(olympic swimmer)** ⇒

d. **Some** student here is a **(swimmer)**



Ladusaw: quantifiers are either UE or DE on each argument

(11) *No – DE on both arguments*

{x: x is an olympic swimmer}⊆{x: x is a swimmer},

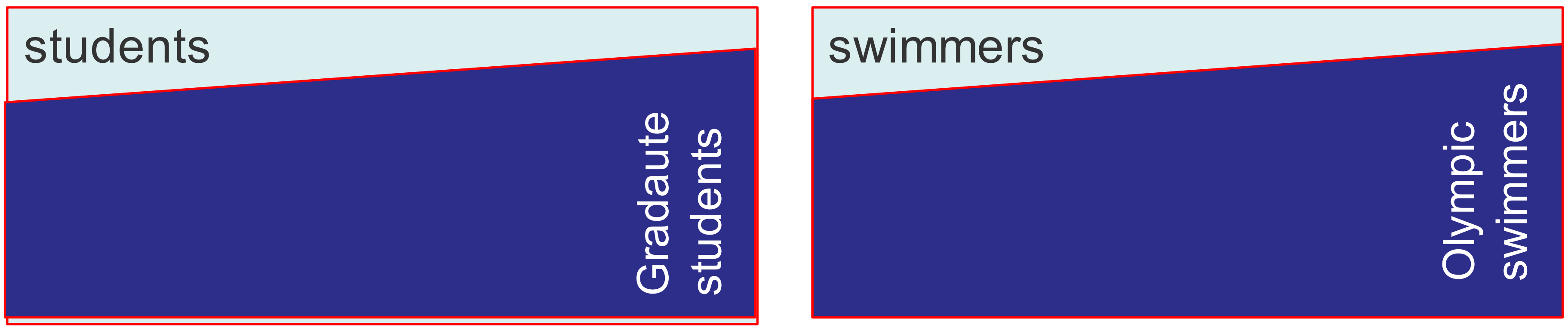
{y: y is a graduate student}⊆{y: y is a student}:

a. **No (student)** (is a swimmer) ⇒

b. **No (graduate student)** is a swimmer

c. **No** student is an **(swimmer)** ⇒

d. **No** student here is a **(olympic swimmer)**



The strange case of **Every**

(12) *from subsets to supersets* ***{olympic swimmer}⊆{swimmer}***:

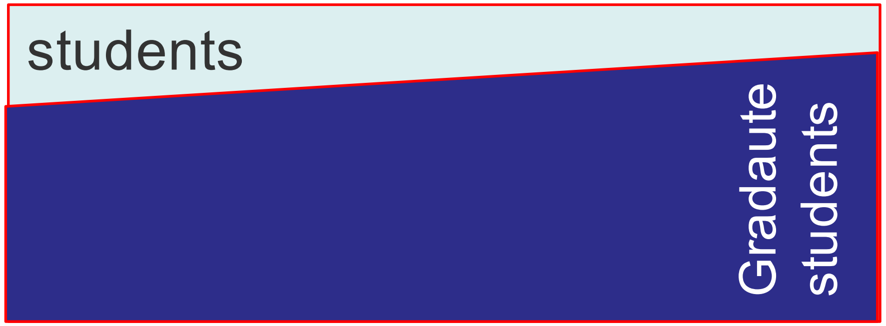
a. **Every** (student) is (**an olympic swimmer**) ⇒

b. **Every** (student) is (**a swimmer**)

(13) *from supersets to subsets* ***{graduate student}⊆{student}***:

a. **Every** (**student**) is an olympic swimmer ⇒

b. **Every** (**graduate student**) is a swimmer

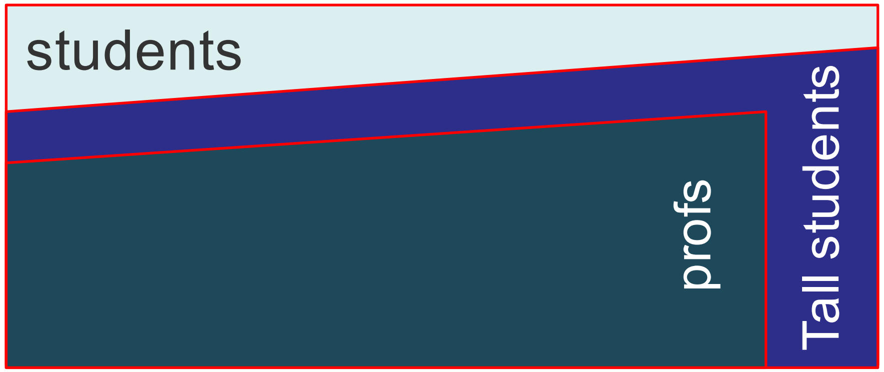


Back to comparatives

(14) *from subsets to supersets* ***{tall student}*⊆*{student}***:

a. there are **more** (**tall students**) than there are (professors) ⇒

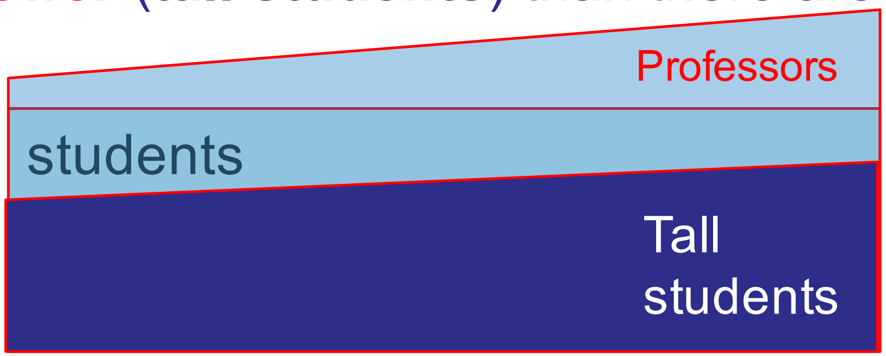
b. there are **more** (**students**) than there are (professors)



(15) *from supersets to subsets* ***{tall student}*⊆*{student}***:

a. there are **fewer** (**students**) than there are (professors) ⇒

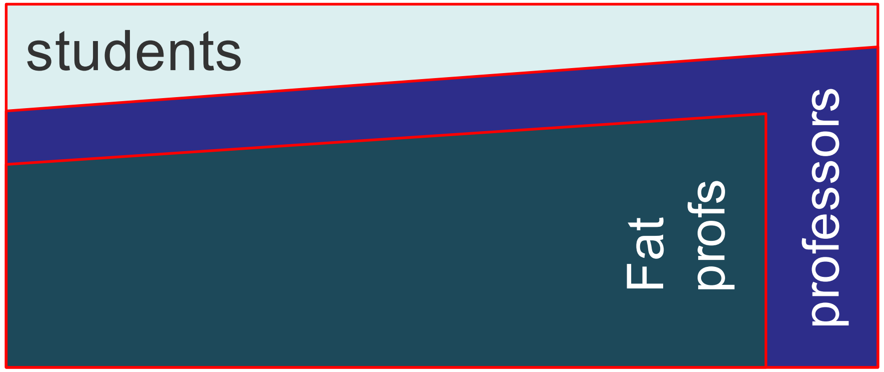
b. there are **fewer** (**tall students**) than there are (professors)



(16) *from subsets to supersets* ***{fat prof}*** $\subseteq$ ***{prof}***:

a. there are **more** (students) than there are (**professors**) $\Rightarrow$

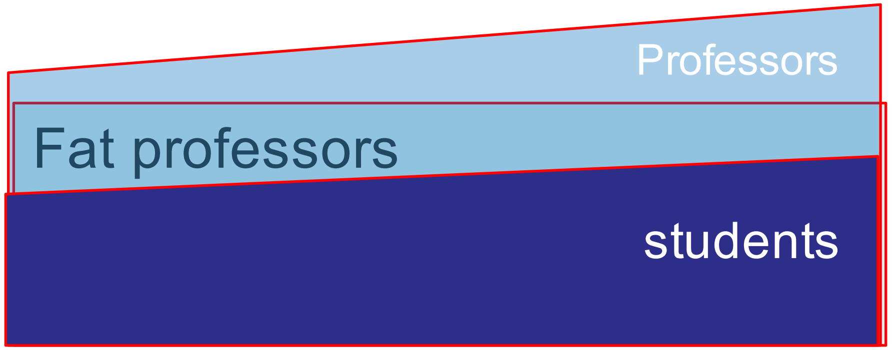
b. there are **more** (students) than there are (**fat professors**)



(17) *from supersets to subsets* ***{fat prof}*** $\subseteq$ ***{prof}***:

a. there are **fewer** (students) than there are (**fat professors**) $\Rightarrow$

b. there are **fewer** (students) than there are (**professors**)



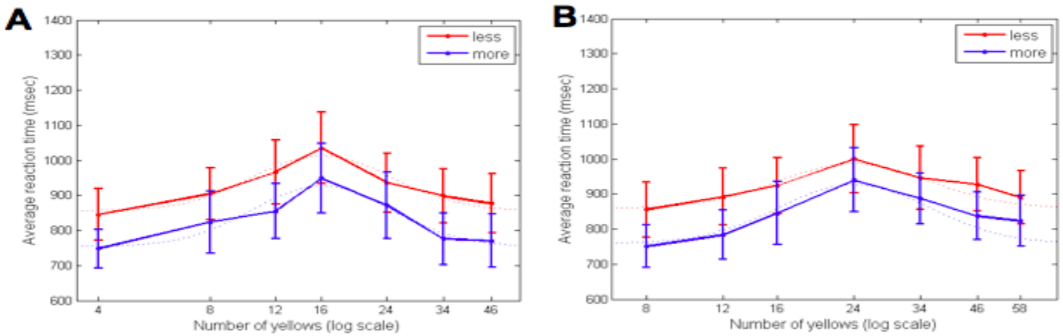
But wait: do we really expect a "polarity effect" in comparatives?

POS:

There are more blue circles than (there are) yellow circles

NEG:

There are fewer blue circles than (there are) yellow circles



(18) a. *More [(there are) blue circles]^{UE} than [(there are) yellow circles]^{DE}*

b. *Fewer [(there are) blue circles]^{DE} than [(there are) yellow circles]^{UE}*

(19) Polarity effect: **$\Delta RT = RT_{DE} - RT_{UE} >^{sig} 0$.**

Two possible accounts of this puzzle

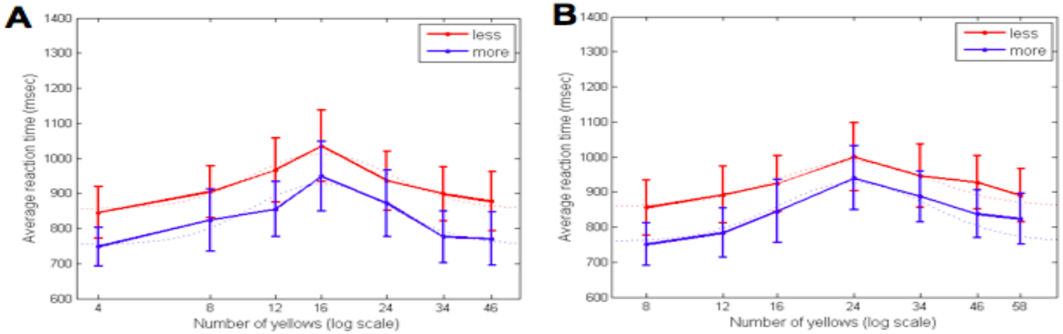
1. Experimental (silly but may be true):

POS:

There are more blue circles than (there are) yellow circles

NEG:

There are fewer blue circles than (there are) yellow circles



To test for this possibility, we are currently running an experiment in which there are circles in 3 colors. This forces participants to wait for the last word in the stimulus.

2. Theoretical The pieces of comparatives and NPIs – the Seuren/Rullman puzzle and a solution that would be consistent with our results

(20) *As expected, NPIs are licensed only in the DE* part:

a. there are **more** (students) than there are (**profs I've *ever*$_{NPI}$ met**)

b. *there are **more** (**students I've *ever*$_{NPI}$ met**) than there are (profs)

c. there are **fewer** (**students I've *ever*$_{NPI}$ met**) than there are (**profs**)

(21) *Unexpected is NPI licensing in the UE part of less-comparatives*:

a. there are **fewer** (students) than there are (**profs I've *ever*$_{NPI}$ met**)

(22) *This pattern follows if the entailment properties are*:

a. More [(there are) blue circles]$^{\mathbf{UE}}$ than [(there are) yellow circles]$^{\mathbf{DE}}$

b. Fewer [(there are) blue circles]$^{\mathbf{DE}}$ than [(there are) yellow circles]$^{\mathbf{DE*DE}}$

(Rullman, Heim)