

Quantifier Polarity Processing and Numerical Comparison: fMRI results show striking Modularity

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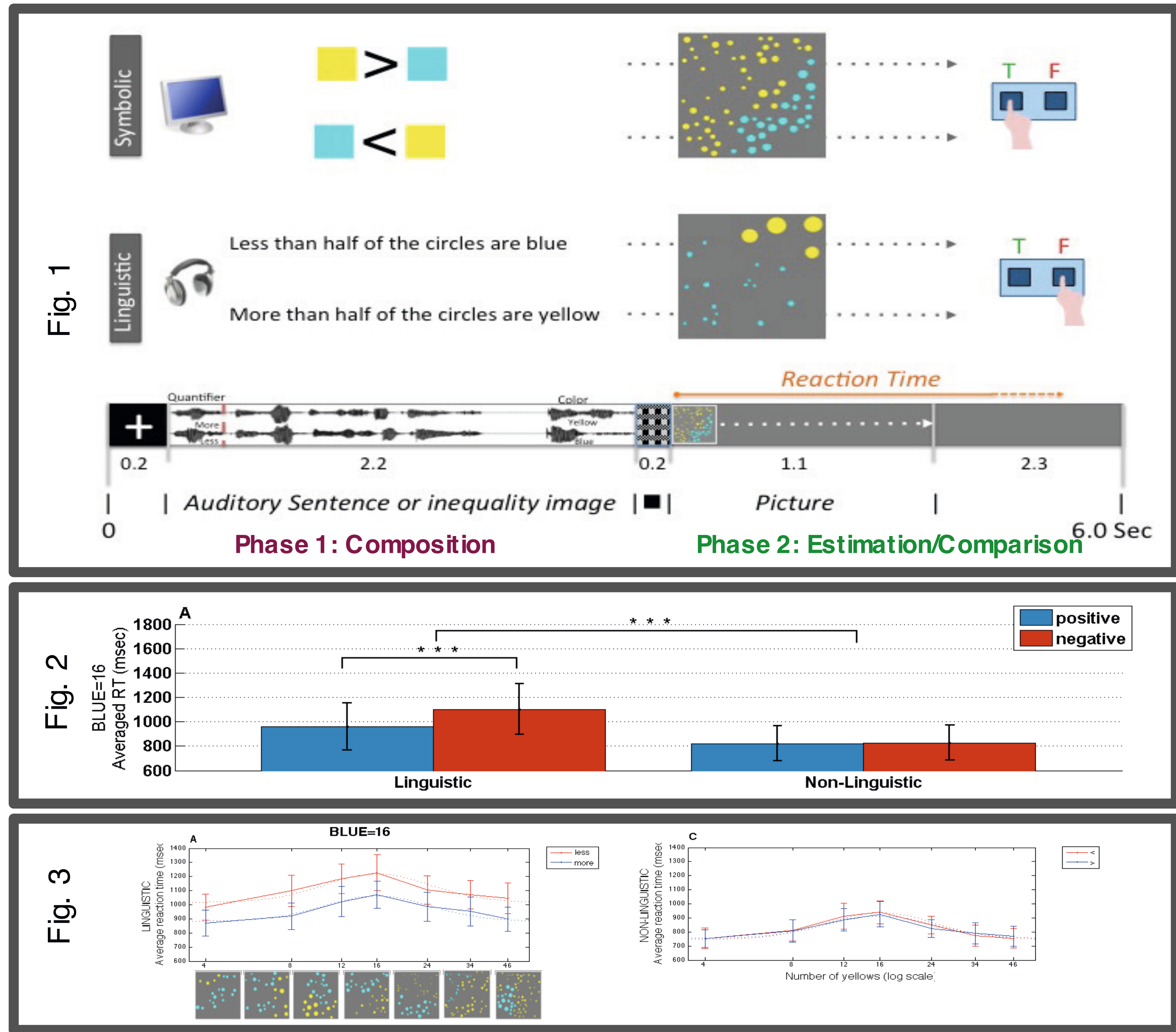
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Introduction

Most work on language/math relations in the brain (e.g., Dehaene et al., 2003, *passim*) focuses on **numbers** and **number words**. Our work studies **complex combinations** in both areas, using combinatorial language and math indices to identify neural relations between the two systems (see Varley et al., 2005).

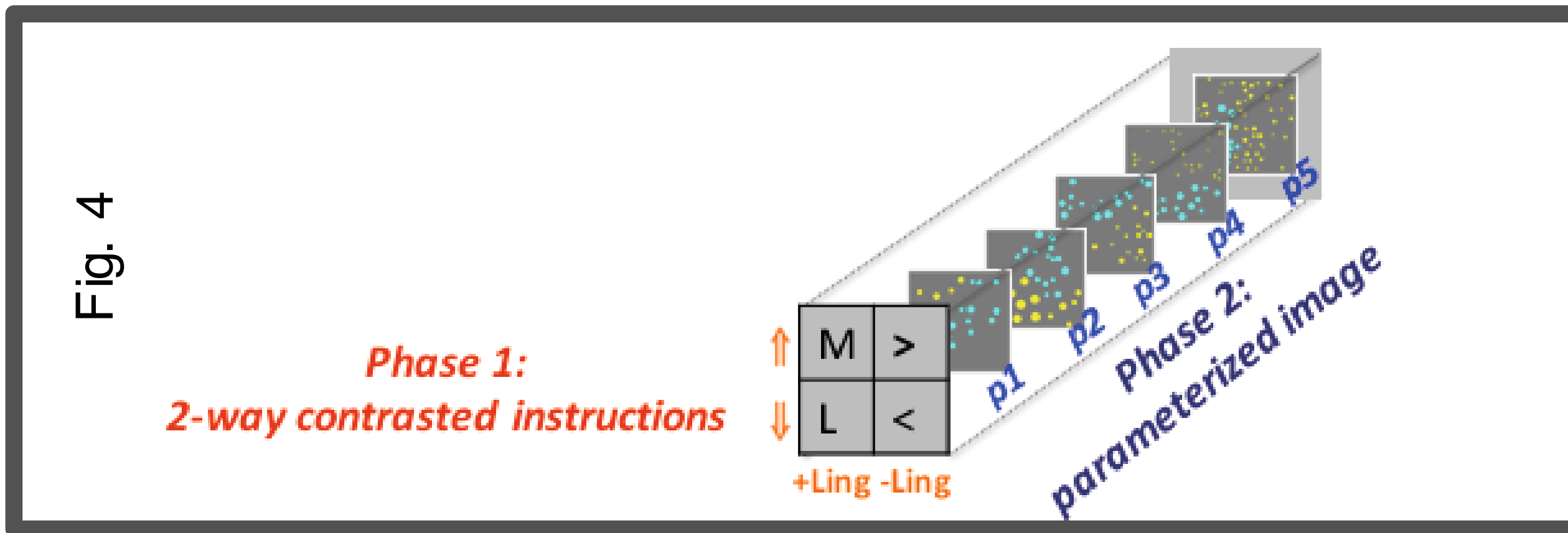
We measured brain activity when sentences with **quantifiers** (*more-than-½*, *less-than-½*) and inequalities (with $>$, $<$) were verified against images with **proportions between quantities**. Our Combinatorial Language Index was meaning **Composition**, built on quantifier Polarity: quantifiers, but not $>$, $<$, can be positive (*more-than-½*), supporting inferences in one direction; or negative (*less-than-½*), where inference direction reverses. Our Numerosity index was numerical **Estimation/Comparison**. Our recent work (Deschamps et al., 2015; Fig. 1) showed a behavioral effect of meaning Composition (Fig. 2) that is independent from numerical Estimation/Comparison (Fig. 3).



Goal and Methods

Goal: we asked whether these temporally distinct processes are neurally distinct.

Setup: Parametric Proportion Paradigm (Fig. 4), linguistic probe pairs with polar quantifiers (*more-than-½*, *less-than-½*); non-linguistic probe pairs ($>$, $<$); images with 5 proportions.



Task (Fig. 1): Speeded truth-value judgment.

Participants: 21 participants (age: 23.6 \pm 4.5, 13 females, all native English speakers).

fMRI data acquisition: 3T Siemens Trio; 4 time series (TE= 30ms, TR=2.0, Flip Angle 90°, matrix 64x64, FOV=224x224, slice thickness 3.5mm, isotropic, no gap, 442 volumes); T1-weighted anatomical scan.

Analyses

- Data pre-processed and analysed in AFNI
- 2 time windows were modelled for each trial:

Phase 1: Composition

Phase 2: Estimation /Comparison

- For **Phase 1**, 4 regressors were modelled: +linguistic: *more/less*, -linguistic: $>$, $<$.
- For **Phase 2**, reaction times were entered as amplitude-modulated parametric regressors.
- 2 masks were created, one for each phase:

Phase 1: Instruction*Polarity interaction;

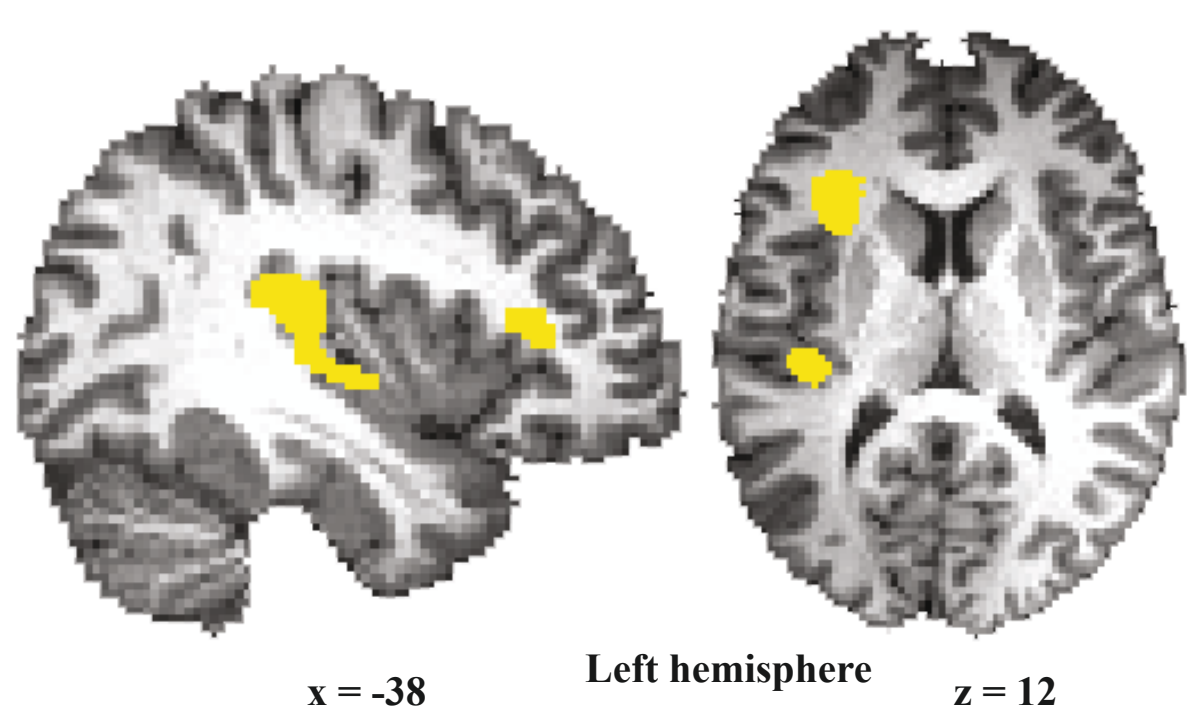
Phase 2: numerical comparison effect (Fig. 5).

- Looked for effects in both masks for both phases

Results

Composition mask

Phase 1: Instruction*Polarity



Phase 2: Instruction*Polarity

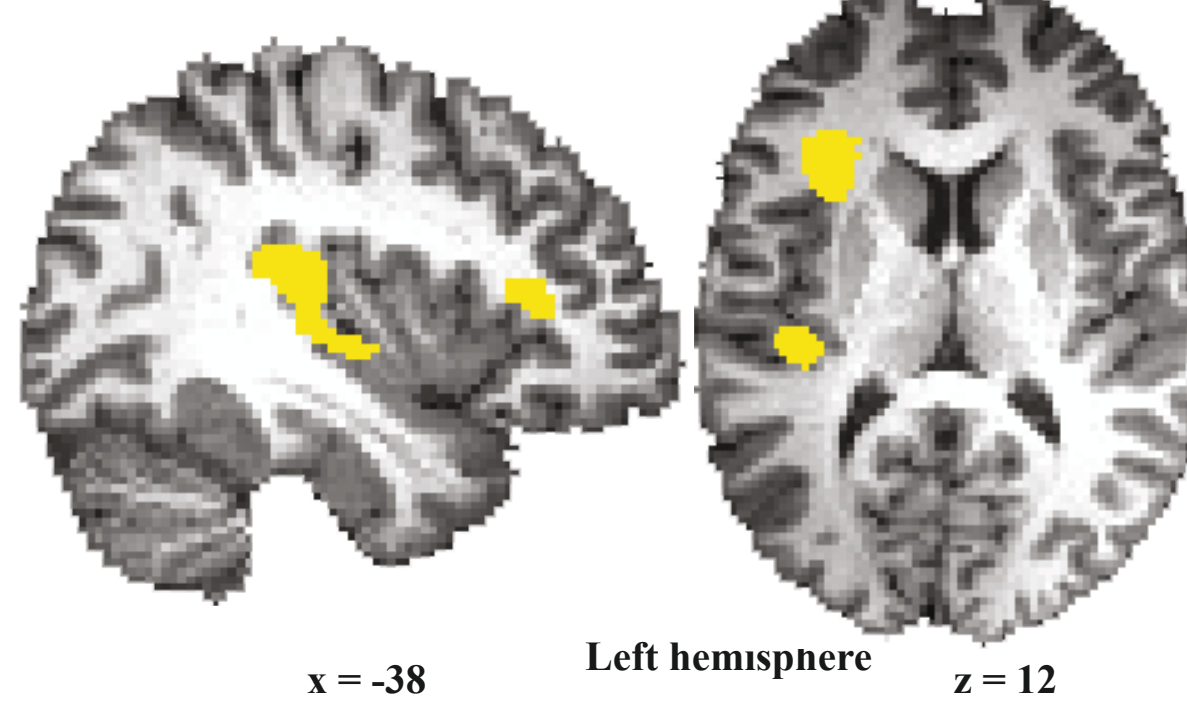
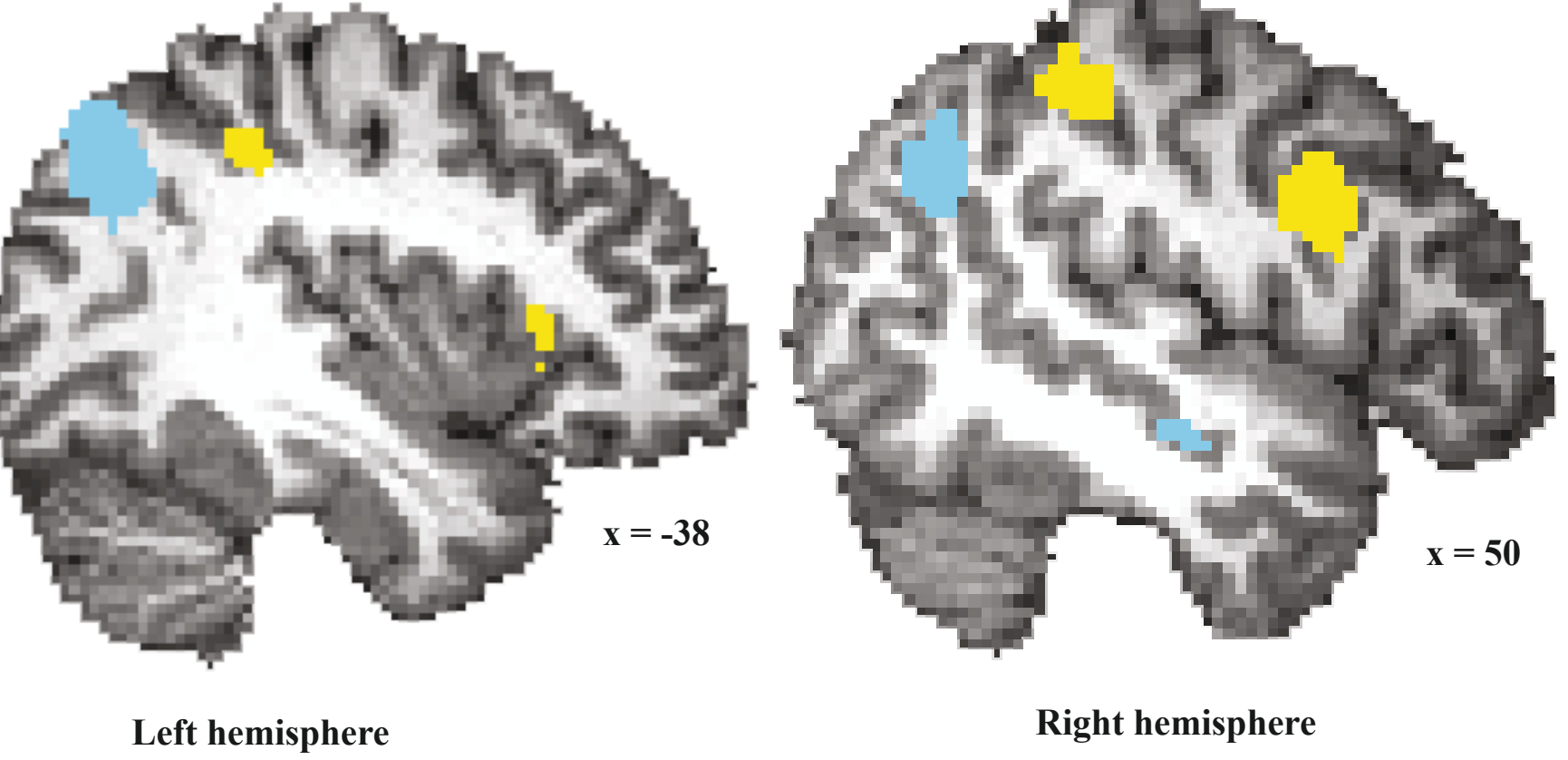


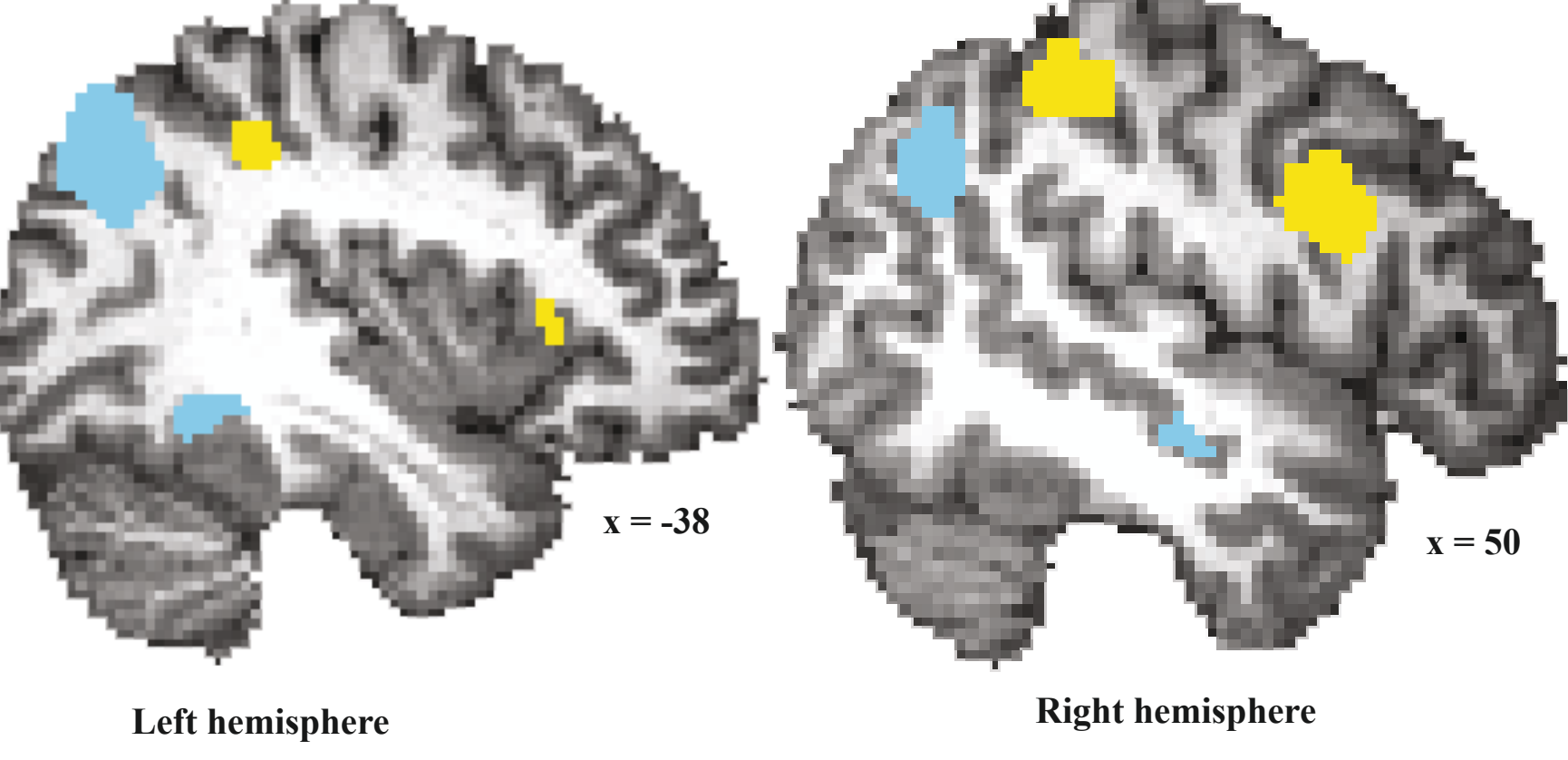
Fig. 5

Estimation /Comparison mask

Phase 1: Effect of numerical comparison



Phase 2: Effect of numerical comparison



- In the **Phase 1** mask, **no** effect of numerical comparison was found during both **Phase 1** and **Phase 2** – (**+Composition**, **-Estimation /Comparison**)
- In the **Phase 2** mask, **no** Instruction*Polarity interaction was found during both **Phase 1** and **Phase 2** – (**-Composition**, **+Estimation /Comparison**)

Discussion

1. Our Combinatorial Language Index – Quantifier Polarity processing, is supported by specialized cortical loci, that are silent during numerosity tasks.
2. Our Numerosity Index, numerical estimation/comparison, relies on a distinct set of regions, which are insensitive to language processing.
3. Critical combinatorial linguistic and numerical abilities constitute distinct neural modules.
4. This linguistic index joins a growing body of evidence on loci for monotonicity.

References: Dehaene, S., et al., *Three parietal circuits for number processing*. Cogn Neuropsychol, 2003. 20(3): p. 487-506. Deschamps, I., et al., *The processing of polar quantifiers, and numerosity perception*. Cognition, 2015. 143: p. 115-28. Varley, R. et al. Agrammatic but numerate. PNAS 102(9), 3519-3524.