

Quantifiers, models, and the role of parietal cortex in a neural theory of interpretation

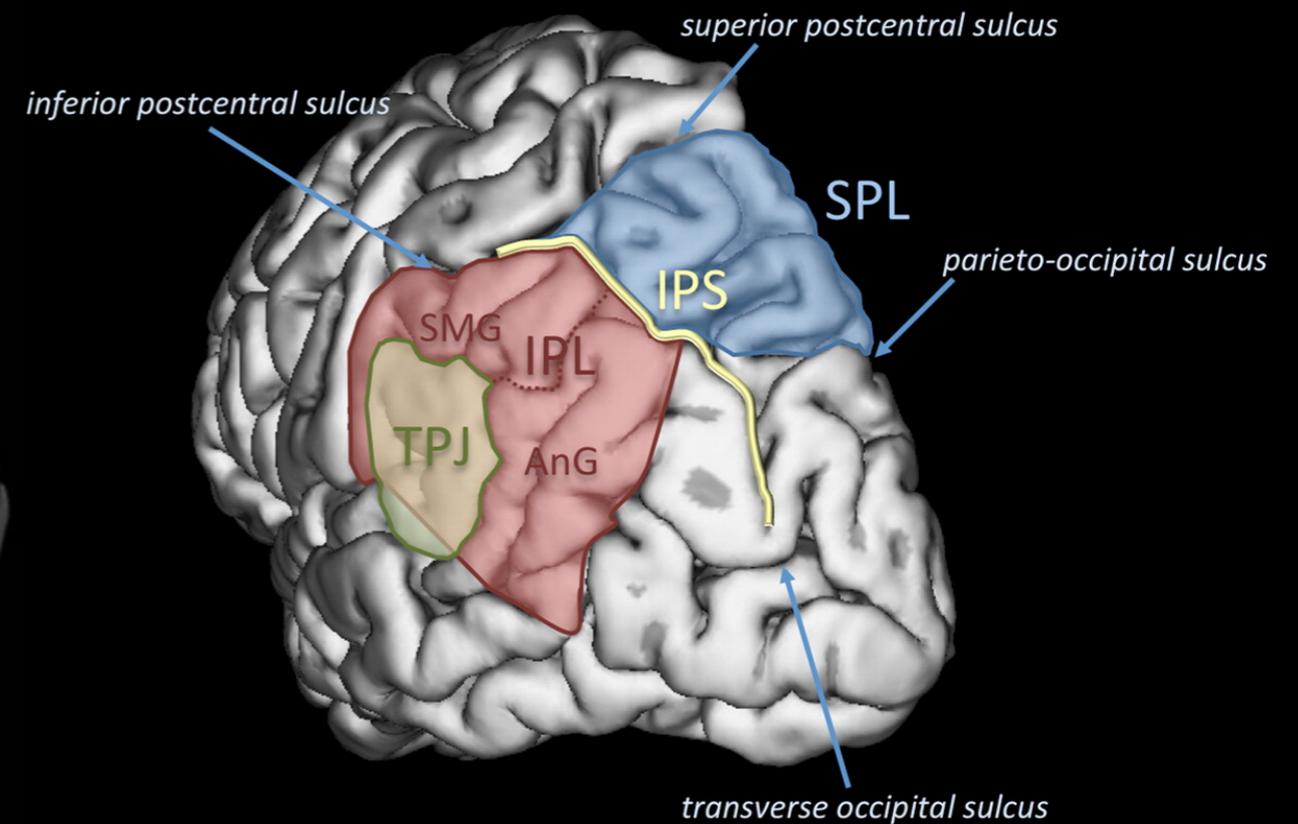
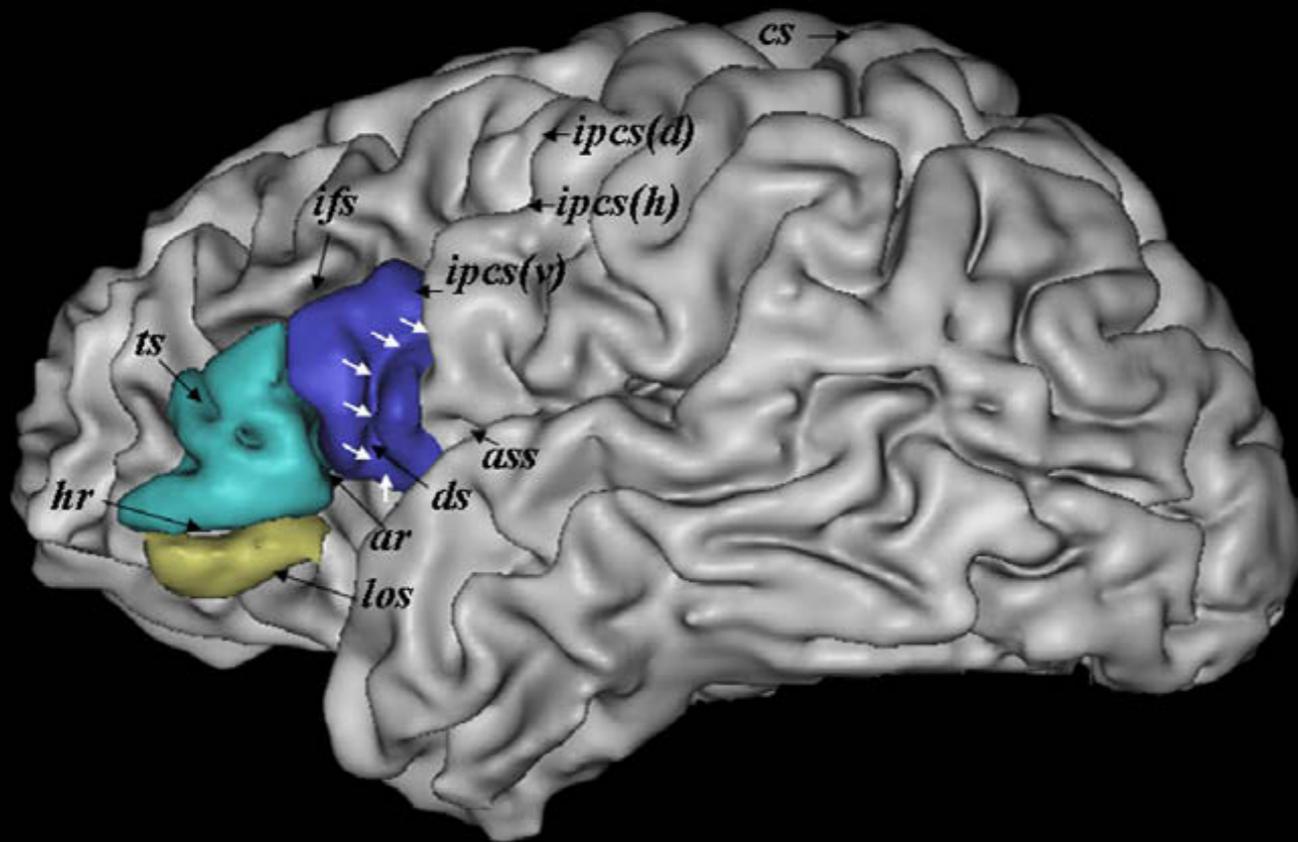
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Cognitive Semantics and Quantities
Amsterdam, September 28-29, 2017



Meaning in the brain



Multiple sub-systems: interplay of temporal, frontal and parietal cortices, limbic and striatal systems; inferior frontal gyrus (pars opercularis, triangularis and orbitalis), inferior parietal lobule etc.

Keller et al. (2009); Hutchinson et al. (2009)

Quantifiers in the brain

- Inferior frontal and inferior parietal networks (McMillan et al. 2005, 2013; Olm et al. 2014); bilateral, lateralization effects
- Correlations between IFG and IPL with numerical quantifiers, MFC and PCC with Aristotelian quantifiers (Troiani et al. 2009)
- ATL activity not modulated by quantifier phrase composition or interpretation (Blanco-Elorrieta & Pylkkänen 2016, MEG)
- Division of labor between IFG and IPL: IFG form and meaning (e.g., ‘many’ vs ‘few’), IPL and IPS numerosity representation (estimation, comparison etc.; Heim et al. 2012, 2015, 2016)
- Back to propositional logic to clarify the functions of IFG, IPL

Propositional connectives in the brain

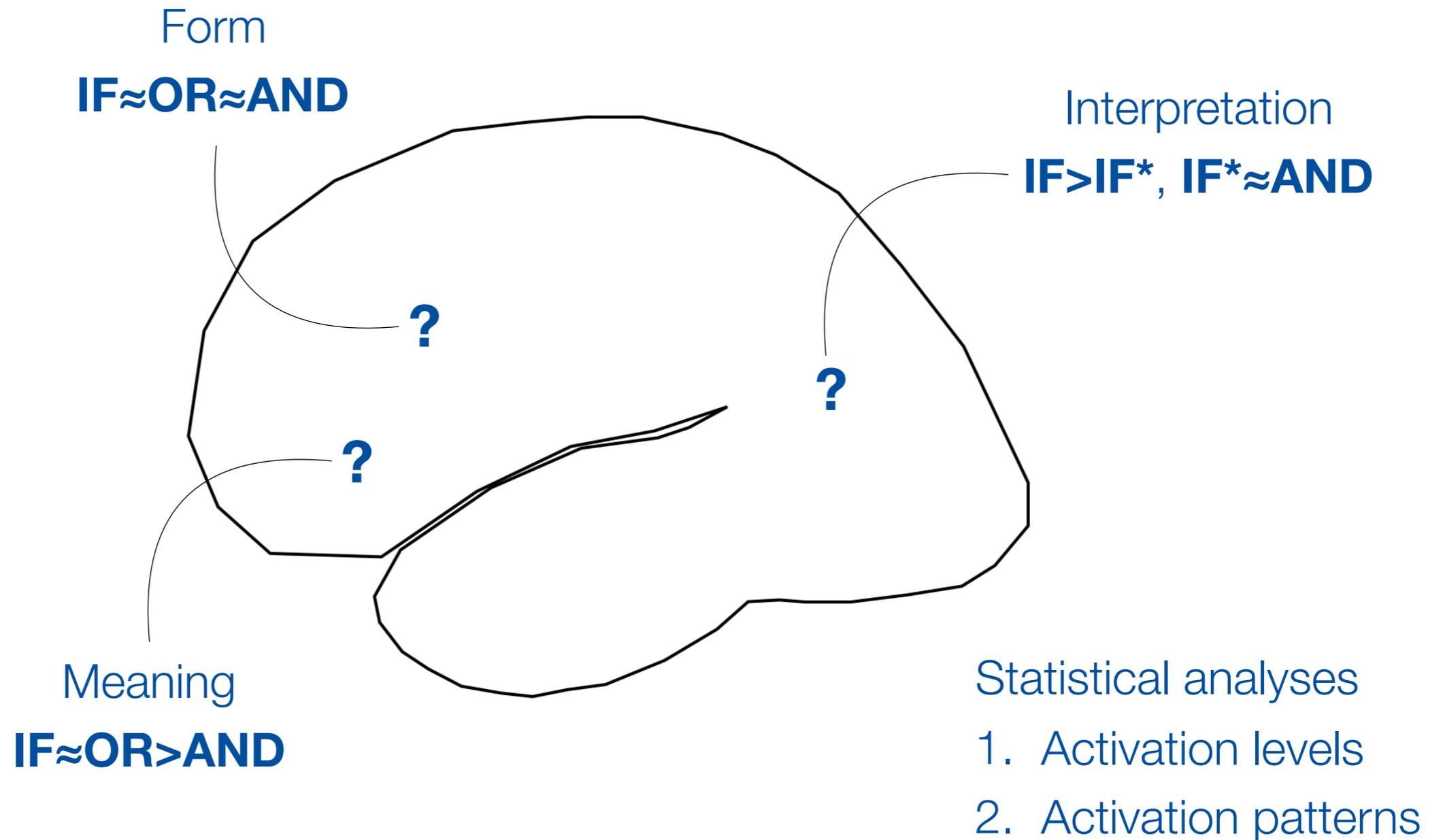
- AND, OR and IF are basic building blocks of cognition: language, reasoning, planning, organization of behavior, strategic interaction, games etc.
- A class of logical constants, much like quantifiers; arguably simpler from a computational and algorithmic perspectives
- Propositional reasoning engages left inferior parietal cortex, adjacent to the parietal number system (Prado et al. 2011)
- The functional link between IPL and quantifier processing may be a special case of a general functional link between IPL and interpretation (models, reference structures)

Propositional connectives in the brain

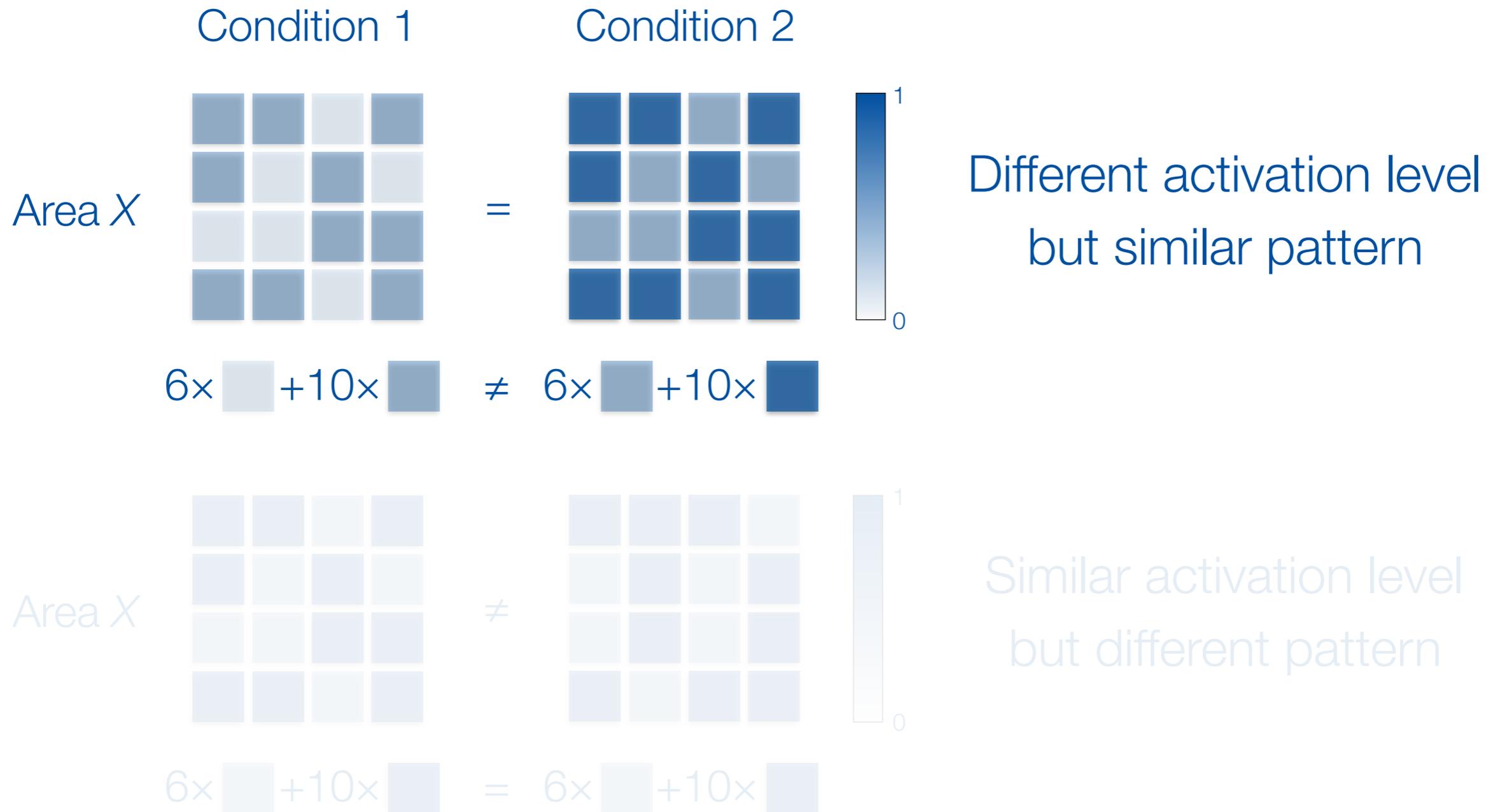
‘Complexity’ at three different levels

- **Form** | AND, OR and IF are all binary operators, similar complexity at the level of surface structure | $IF \approx OR \approx AND$
- **Meaning** | Number of models of a compound: 3 for IF and OR vs 1 for AND (also: semantic information) | $IF \approx OR > AND$
- **Interpretation** | Context-dependent representations, e.g., conditionals, classical vs conjunctive | $IF > IF^*$, $IF^* \approx AND$
- Classical | ‘If p then q’ is false iff ‘p’ is true and ‘q’ is false
- Conjunctive* | ‘If p then q’ extensionally equivalent to ‘p and q’

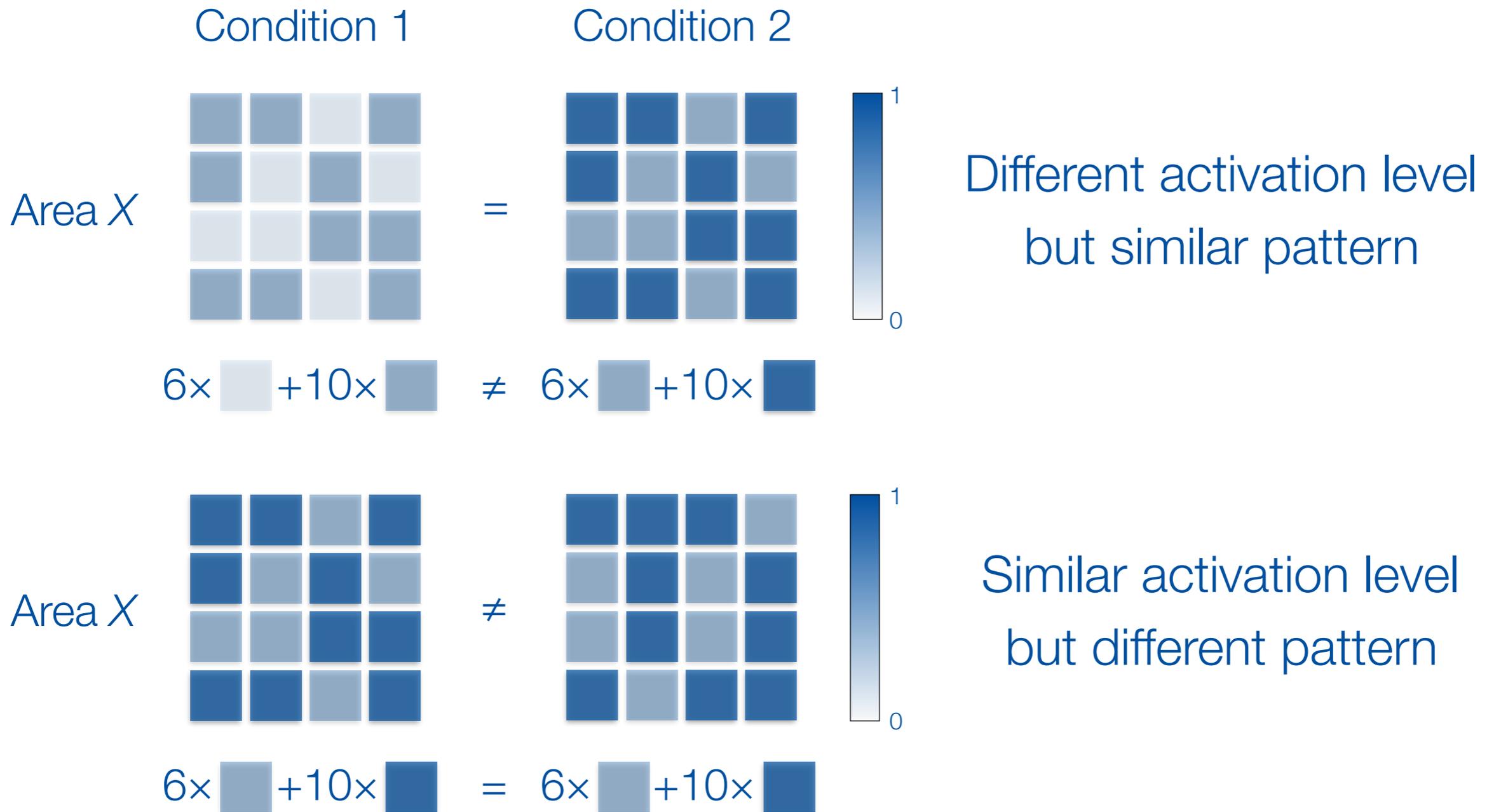
Propositional connectives in the brain



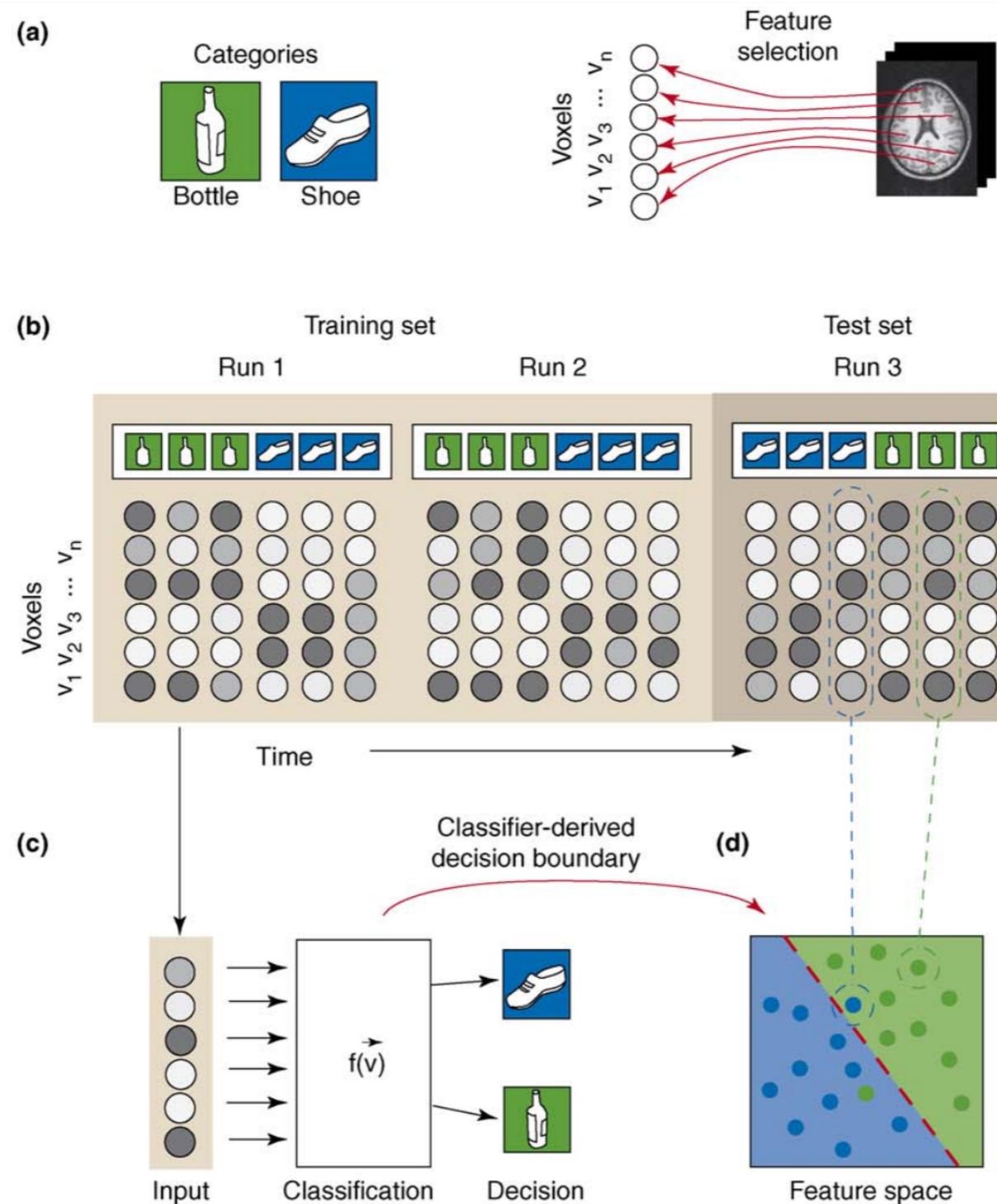
Activation levels vs activation patterns



Activation levels vs activation patterns



Multivoxel pattern analysis (MVPA)



Maintenance and evaluation task

Compounds

AND | There is a yellow square **and** there is a green circle

OR | There is a yellow square **or** there is a green circle

IF | **If** there is a yellow square **then** there is a green circle

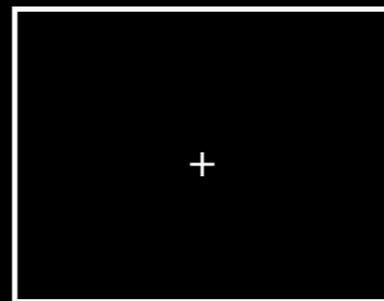
Baseline | Press the key that turns orange

Cues

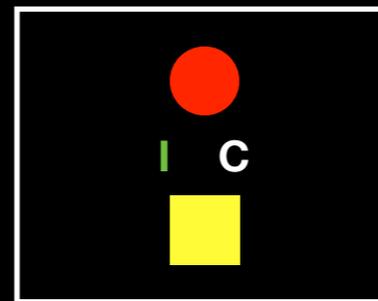


CUE
1000 ms

There is a yellow square
and a green circle

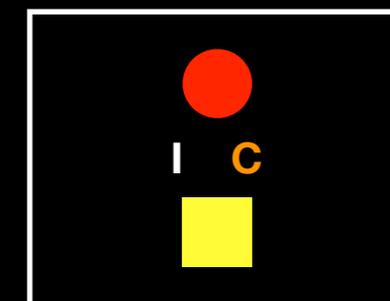


DELAY
6000 ms



TARGET
3000 ms

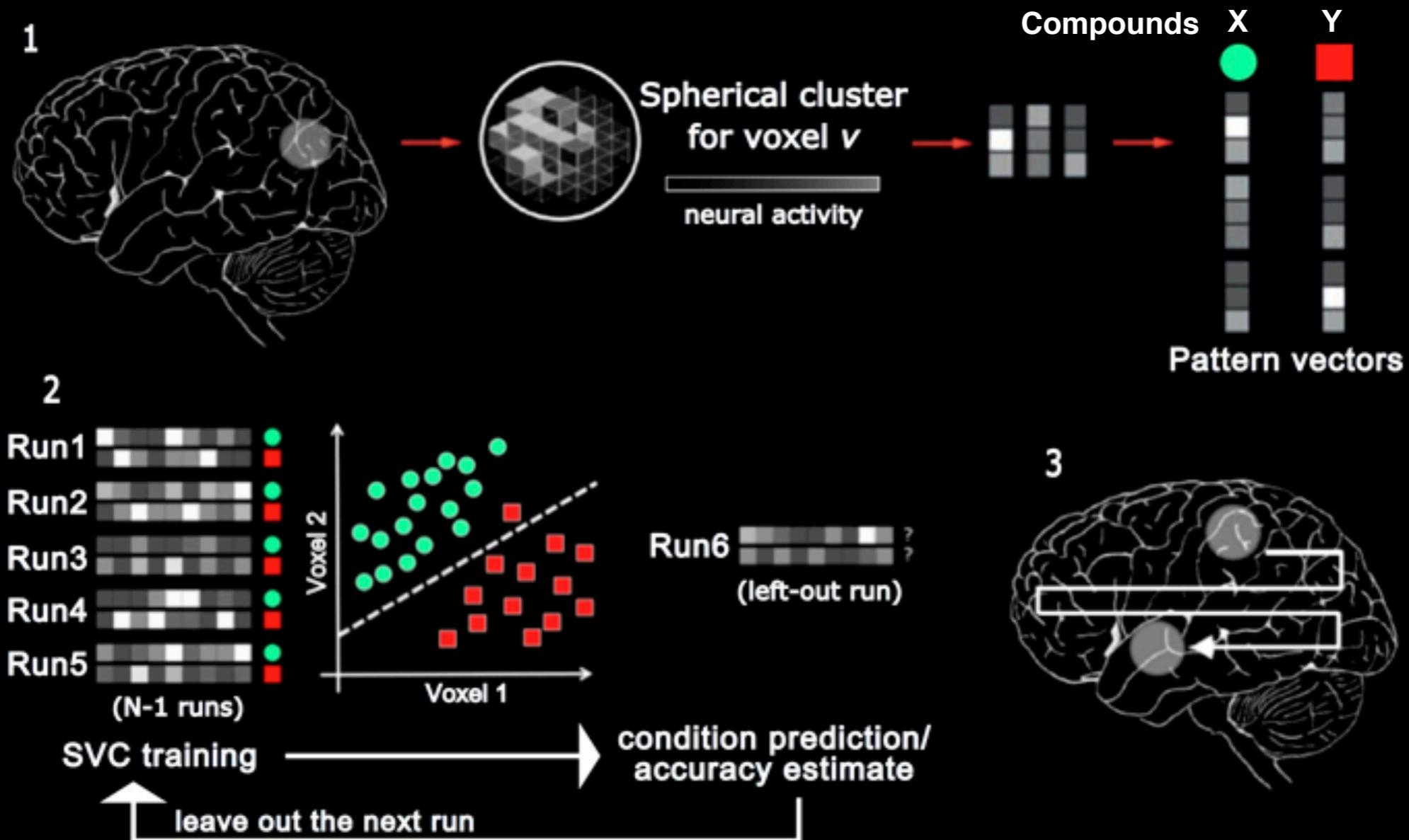
Incompatible **I**
Compatible **C**



TARGET
3000 ms

Baseline task
'Press the key that turns **orange**'

Multivoxel pattern analysis (MVPA)



Behavioral results

Consistency (on correct responses):

AND 89% (SD=4.5%)

OR 89% (SD=3.8%)

IF 91% (SD=4.4%)

Response times ($F(2,58)=49.7, p<.001$):

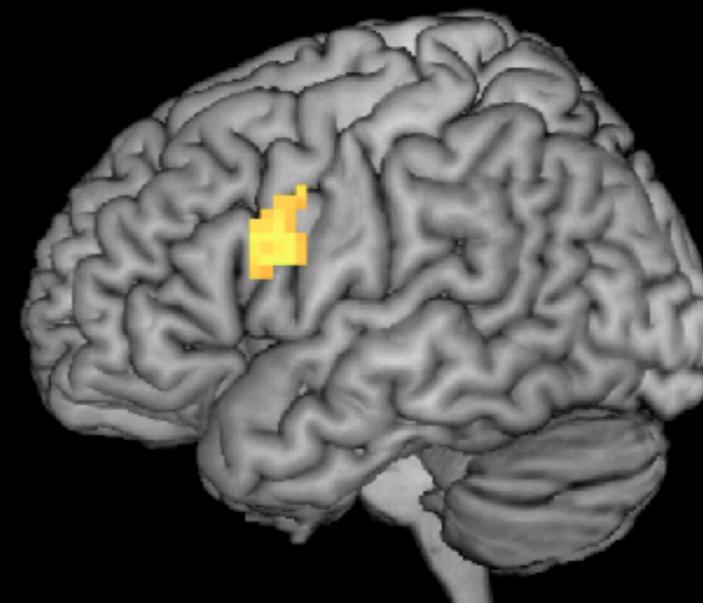
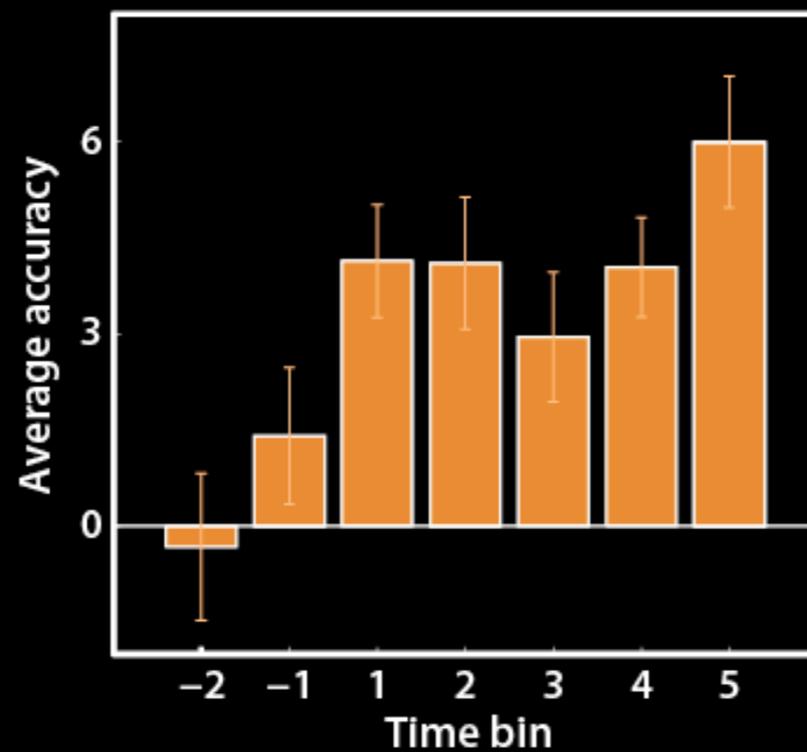
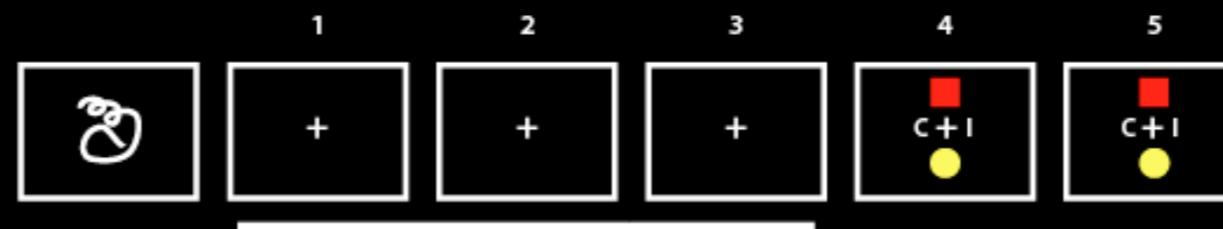
AND 1342 ms (SD=208 ms)

OR 1531 ms (SD=175 ms)

IF 1428 ms (SD=211 ms) [all interpretations]

IF 1540 ms vs **IF*** 1326 ms ($t(27) = 3.0, p=.006$)

Maintenance phase

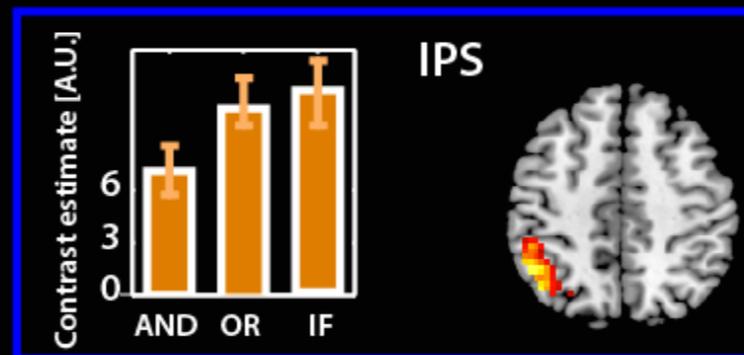


No univariate effects, no pattern similarity differences: **IF \approx OR \approx AND**

Evaluation phase

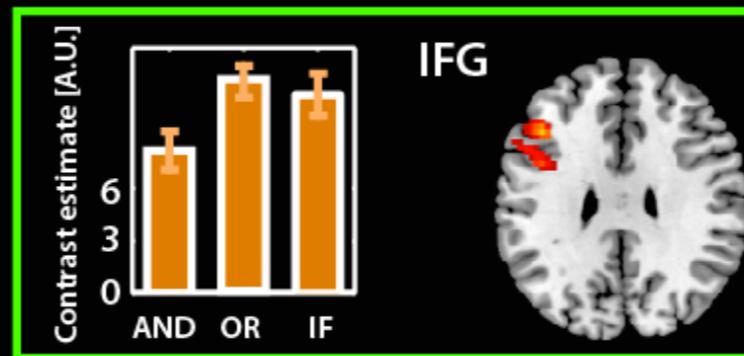
IPS/BA40

IF>AND $t(28) = 4.29, p < .001$
OR>AND $t(28) = 4.66, p < .001$
IF \approx OR $t(28) = .48, p = .63$



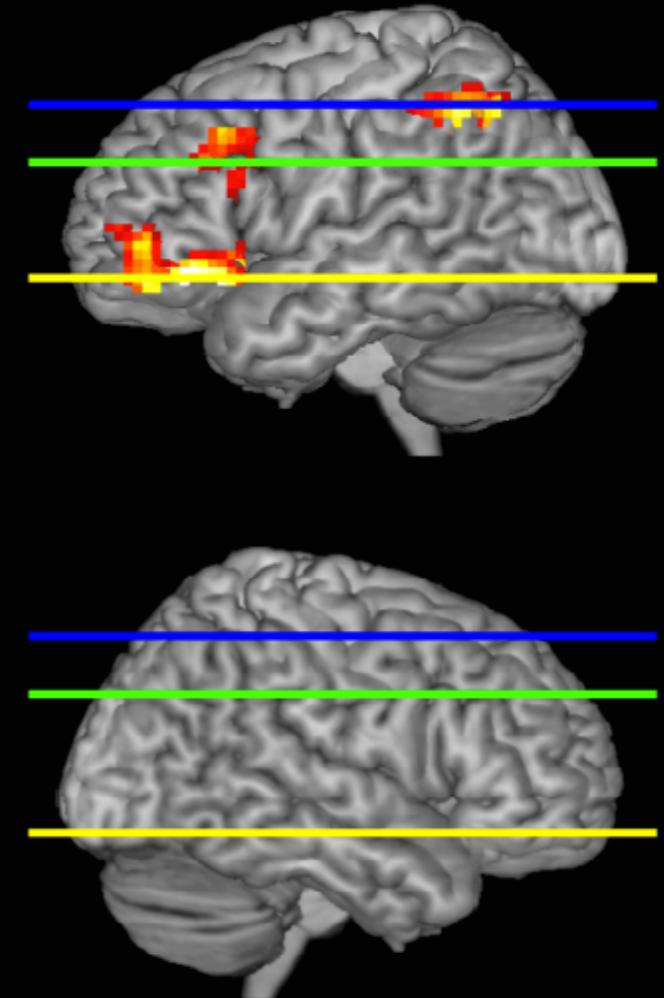
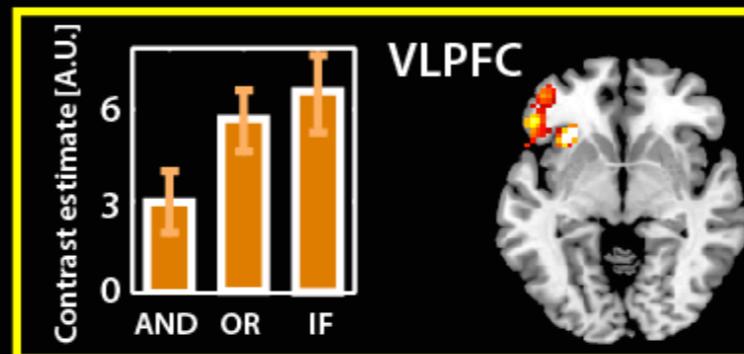
IFG/BA44

IF>AND: $t(28) = 3.36, p = .002$
OR>AND: $t(28) = 4.93, p < .001$
IF \approx OR: $t(28) = -1.05, p = .30$



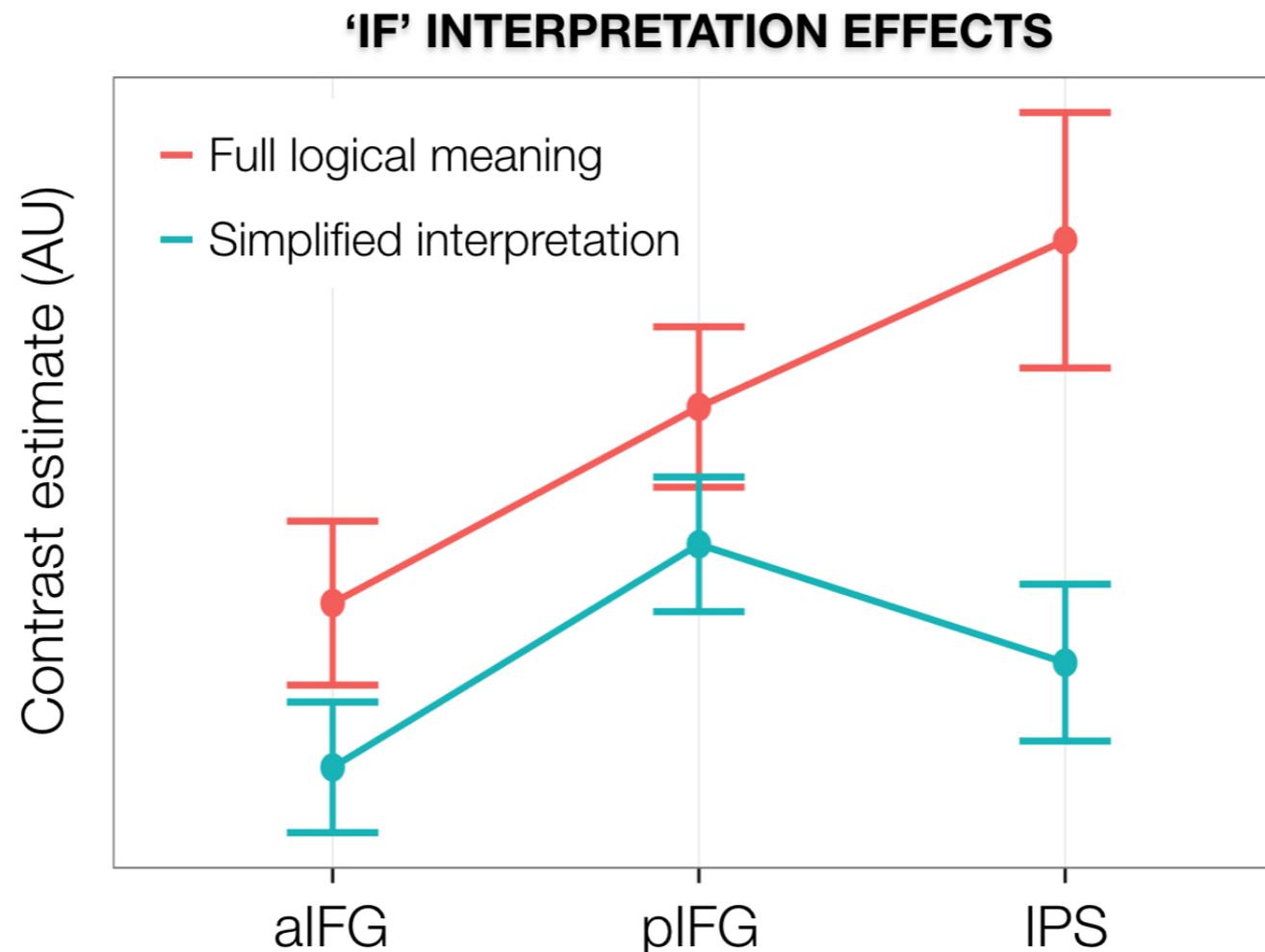
VLPFC/BA47

IF>AND: $t(28) = 5.17, p < .001$
OR>AND: $t(28) = 3.47, p = .002$
IF \approx OR: $t(28) = 1.15, p = .26$



Pattern similarity: IF more similar to OR than to AND; **IF \approx OR>AND**

Evaluation phase



Interaction of ROI by IF-interpretation ($F(2,54)=5.56$, $p=.006$): higher activation in left IPS in full logical interpretation of IF ($t(27)=2.93$, $p=.007$); no effect in left aIFG ($t(27)=1.32$, $p=.20$) and pIFG ($t(27)=1.59$, $p=.12$)

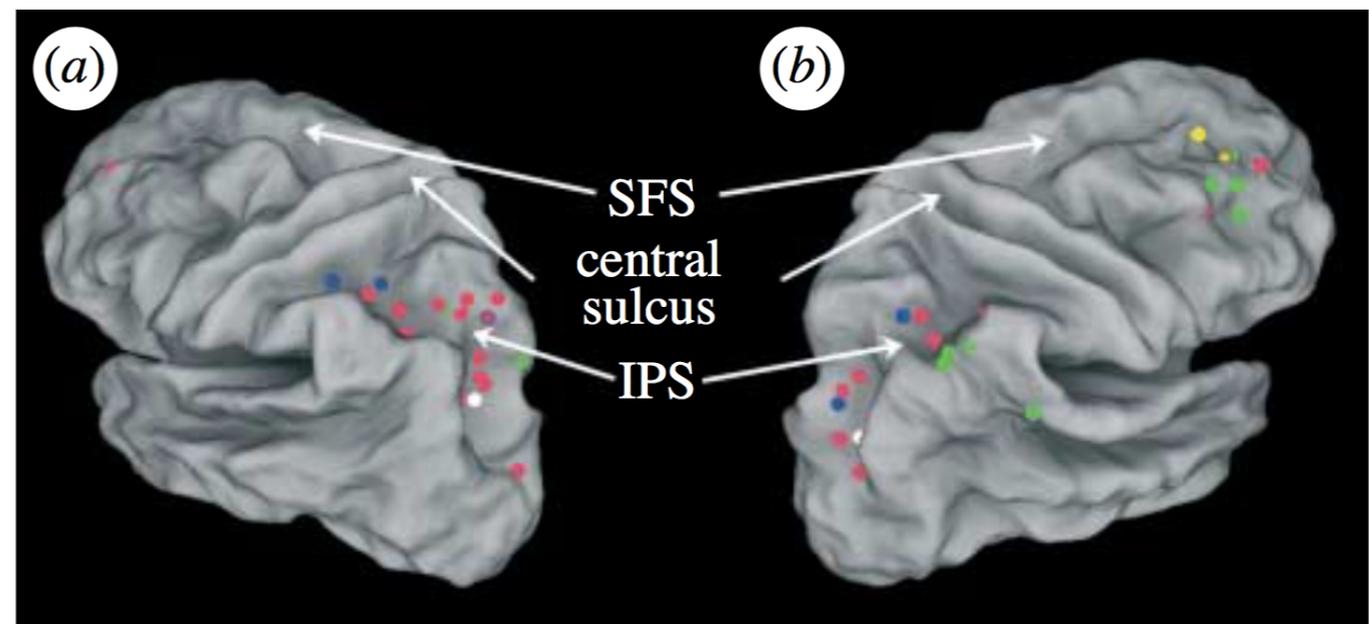
Summary of results

- **Form** | $IF \approx OR \approx AND$ | **pIFG** the only cortical region showing a decoding effect during delay, and no univariate or RS effects
- **Meaning** | $IF \approx OR > AND$ | **pIFG+alFG+IPS** network showing similar activation levels and spatial patterns for IF and OR
- **Interpretation** | $IF \neq IF^*$, $IF^* \approx AND$ | **IPS** the only area where activation levels differ between logical IF and conjunctive IF^*
- Dynamic coding | pIFG (Broca's area) can rapidly switch between two codes: surface form and logical meaning
- Distributed coding | Left-lateralized IFG+IPL network processes logical form and meaning, beyond quantifiers

Interpretation in the brain

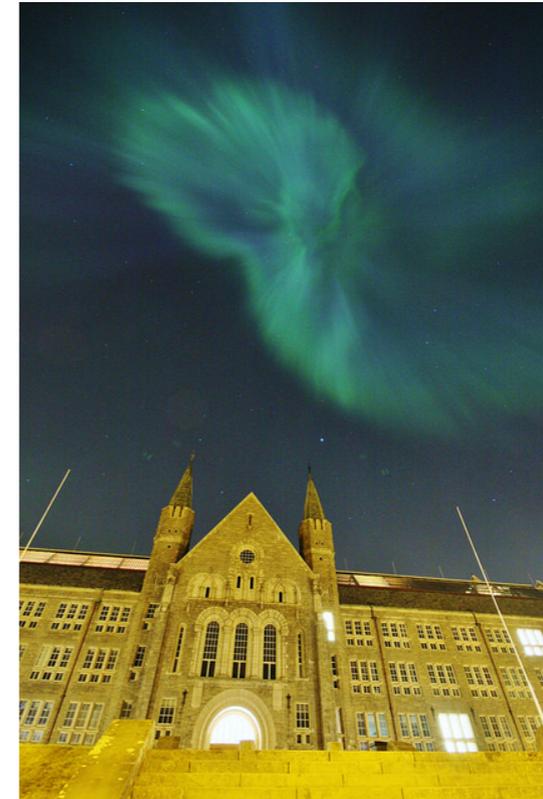
- **Interpretation** | Mapping a logical representation of an expression onto a representation of a reference structure
- Interplay between IFG and IPL (abstract magnitude system) is crucial for interpreting referring expressions; IPL reference structure, scanning through (elements of) reference structures

- Size
- Time
- Space
- Number
- Luminance



Walsh (2003); Buetti & Walsh (2009)

Thanks!



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G. Baggio, P. Cherubini, D. Pischedda, A. Blumenthal, J.D. Haynes & C. Reverberi (2016) Multiple neural representations of elementary logical connectives. *NeuroImage* 135, 300-310

G. Baggio (2018) *Meaning in the Brain*. The MIT Press.