Probabilistic Logic for Coordinate-Based Meta-Analysis of Functional Segregation in the Brain

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Introduction:

Accurately mapping cognitive processes to distinct brain regions [1-3] requires meta-analytic synthesis of neuroimaging databases [4-6], which have become crucial to human brain mapping. However, current meta-analytic query systems are limited to expressions of already known facts, which precludes the generation of new knowledge about functional segregation in the brain. A novel framework using a probabilistic logic programming tool called NeuroLang overcomes this shortcoming, enabling an expressively-rich formalism of functional segregation queries in a natural language syntax, while endowing results with probabilities of them being true.

Here, we leverage the expressive power of NeuroLang to study the functional segragation in the posterior cingulate cortex (PCC). A central node in the default mode network [8], the PCC is widely known to subserve internally-directed cognitive processes [9]. However, recent evidence suggests that this region is associated with disparate cognitive processes [5,9], with the dorsal PCC involved in cognitive control and ventral PCC supporting internally-directed cognition. The approach showcased in this study provides a tool that can validate

findings and enable future investigations into uncharted brain regions.

Methods:

We use NeuroLang, a domain-specific probabilistic logic programming language [7], able to express complex reverse inference queries on CBMA databases. Reverse inference asks which terms, generally associated with cognitive processes, are most probably associated with a given activation pattern. We use the DiFuMo functional parcellation [10] to define two subregions of the PCC. For the CBMA database, we use NeuroQuery [3]. NeuroQuery calculates term-to-study associations from the full text of studies and is well-suited for reverse inference.
Peak activation coordinates and term-to-study associations reported by studies in the database are encoded in NeuroLang, alongside DiFuMo regions. Predicate logic allows us to represent this knowledge, using predicates such as TermAssociation(visual, 18183754), that encodes that study 18183754 is associated with the term 'visual'. Queries on this program can be expressed and used to infer new knowledge.
Solving a reverse inference query is done by estimating conditional probabilities P[TermAssociation(t, s) | Q] of term t being associated with study s, given a query Q over CBMA data. To differentiate function across PCC subregions, we define Q as a segregation query that selects studies reporting activations in a PCC subregions but not in the other one (i.e. segregating the other component). More formally, this is written as
P[TermAssociation(t, s) | RegionReported(vPCC, s) ∧ ¬RegionReported(dPCC, s)]
where '¬' is the logic negation operator. This is done for the vPCC, segregating the dPCC, and vice-versa. We run this query and analyse the resulting probabilities to identify cognitive functions most probably associated with each subregion, while performing subsampling of all NeuroQuery studies to derive empirical probability distributions(Fig. 2).

Results:

Consistent with recent evidence [9], our results suggest differential involvements of d-/v PCC in cognition(Fig. 2) Particularly, terms generally associated with "Cognitive Control" are more likely to appear in studies that report only dPCC and not vPCC activations. In contrast, terms associated with internally-directed cognitive processes, such as "Self Reference", are more likely to appear in studies reporting only vPCC and not dPCC activations. A code to replicate the findings can be found in [11].

Conclusions:

In this study, we used probabilistic first-order logic to assess the functional segregation in the PCC, with findings supporting recent evidence of differential roles for d-/v PCC. Through this methodological approach, we hope to empower the cognitive neuroscience community with an expressive and powerful language that can aid in exploring and developing new hypotheses of brain-behavior relationships.

Modeling and Analysis Methods:

Methods Development [1]

Neuroanatomy, Physiology, Metabolism and Neurotransmission:

Anatomy and Functional Systems
Cortical Anatomy and Brain Mapping [2]

Neuroinformatics and Data Sharing:

Databasing and Data Sharing

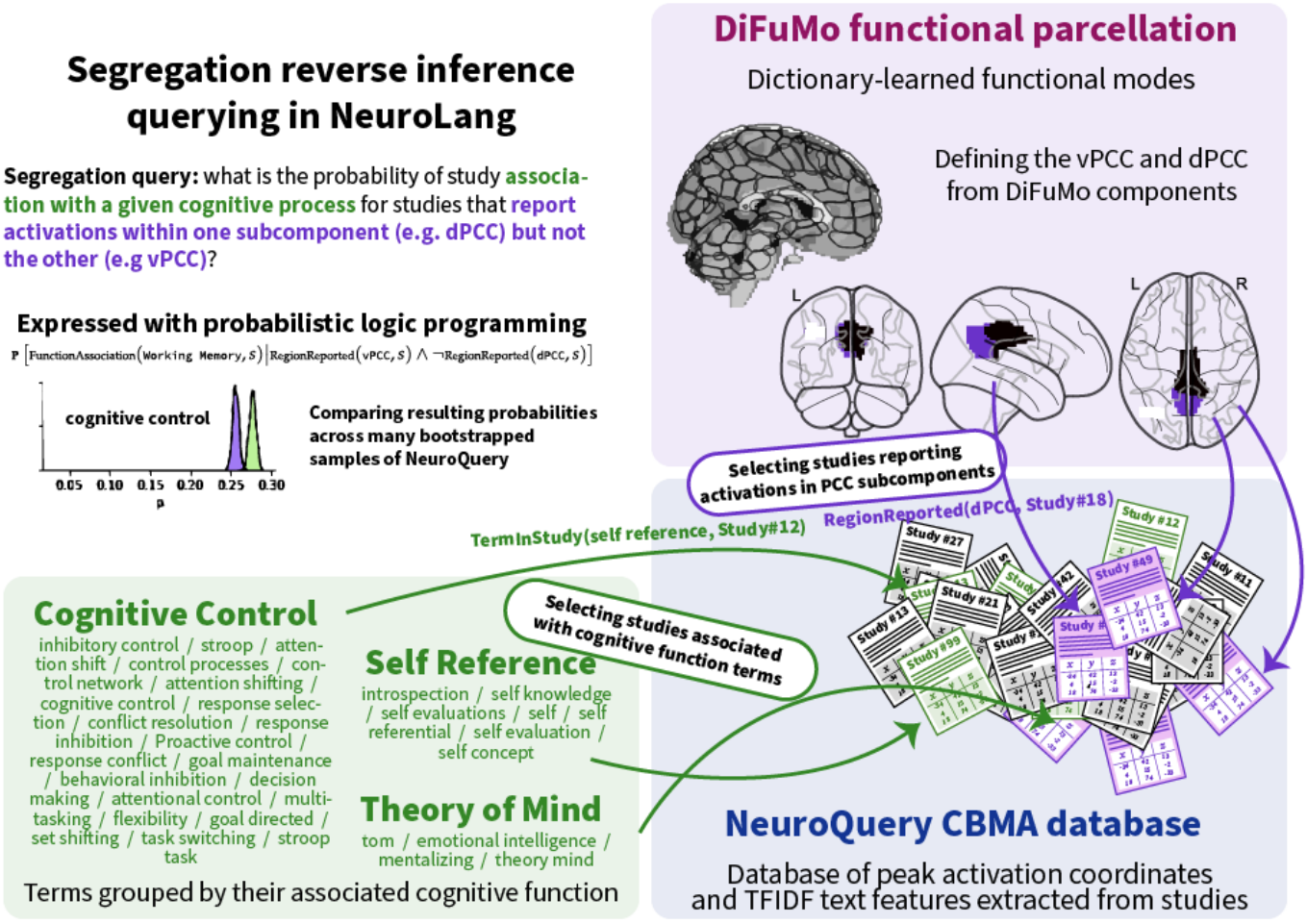
Workflows

Keywords:

FUNCTIONAL MRI
Informatics
Meta- Analysis
Open-Source Code
Open-Source Software
Workflows
Other - Coordinate-based meta-analysis

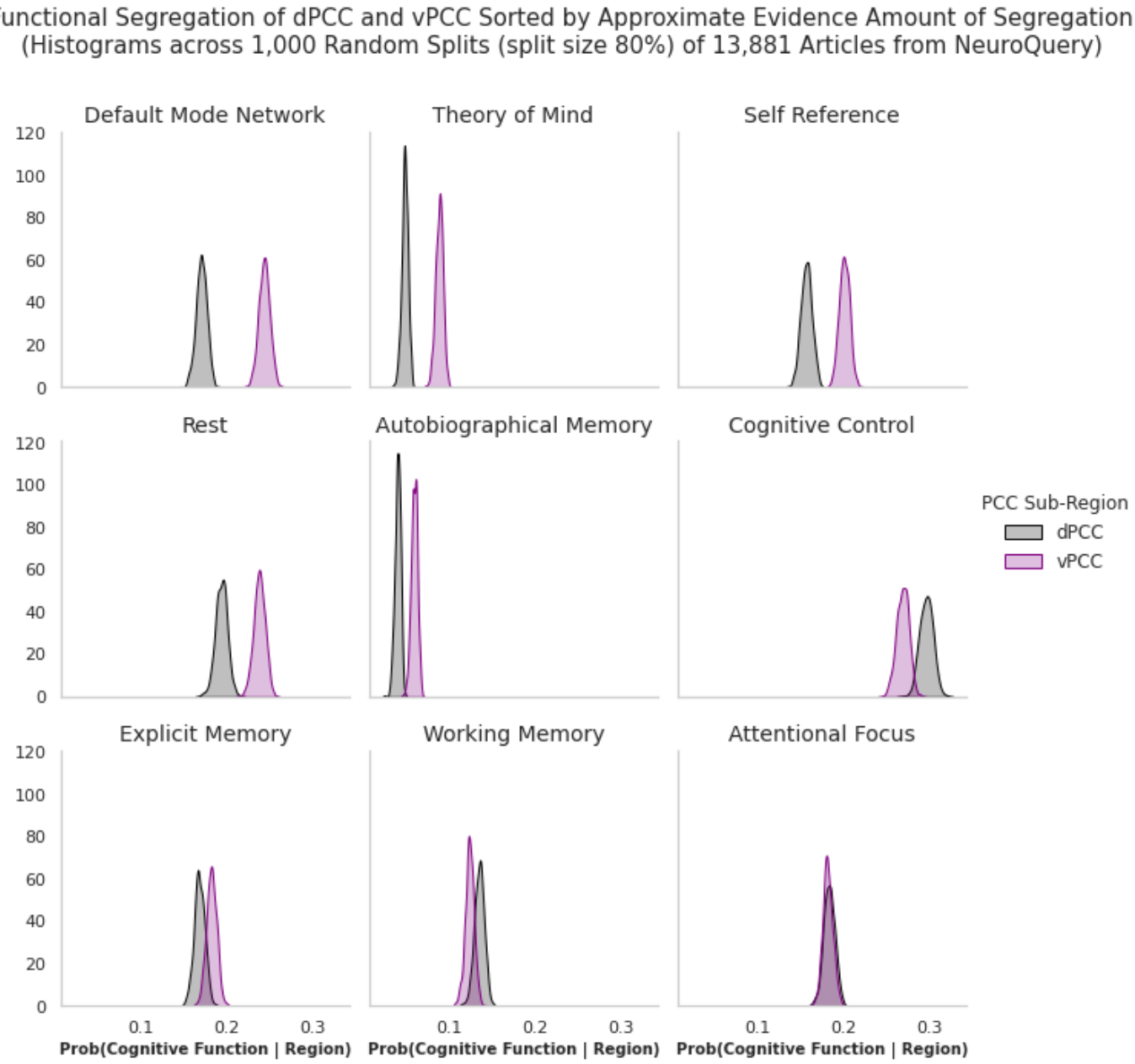
[1|2]Indicates the priority used for review

Graphical Abstract: *Application Example*
Using **NeuroLang** to differentiate functions of the vPCC and dPCC through meta-analytical reverse inference



(https://files.aievolution.com/prd/hbm2101/abstracts/abs_2410/2021-01-ohbm-graphical-abstract-01.png)

·A graphical abstract of the study describing its methodology



(https://files.aievolution.com/prd/hbm2101/abstracts/abs_2410/facet_plot_histograms.png)

·Results of the reverse inference segregation query showing approximate evidence amount of functional segregation between dorsal and ventral PCC across disparate cognitive domains

My abstract is being submitted as a Software Demonstration.

No

Please indicate below if your study was a "resting state" or "task-activation" study.

Other

Healthy subjects only or patients (note that patient studies may also involve healthy subjects):

Healthy subjects

Was any human subjects research approved by the relevant Institutional Review Board or ethics panel? NOTE: Any human subjects studies without IRB approval will be automatically rejected.

Not applicable

Was any animal research approved by the relevant IACUC or other animal research panel? NOTE: Any animal studies without IACUC approval will be automatically rejected.

Not applicable

Please indicate which methods were used in your research:

Other, Please specify - Coordinate-based meta-analysi and probabilistic first-order logic programming

For human MRI, what field strength scanner do you use?

If Other, please list - Not applicable

Which processing packages did you use for your study?

Other, Please list - Not applicable

Provide references using author date format

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/PCC_functional_specialization_example_Difumo_ROI.py