A meta-analysis study on deductive and inductive reasoning using Log-Gaussian Cox Processes

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Research Question

- **What would be easier, faster, and reliable model-based methods in meta-analysis?**
- **How are deductive and inductive reasoning represented in human brain?**

Background

Combining inductive and deductive Reasoning

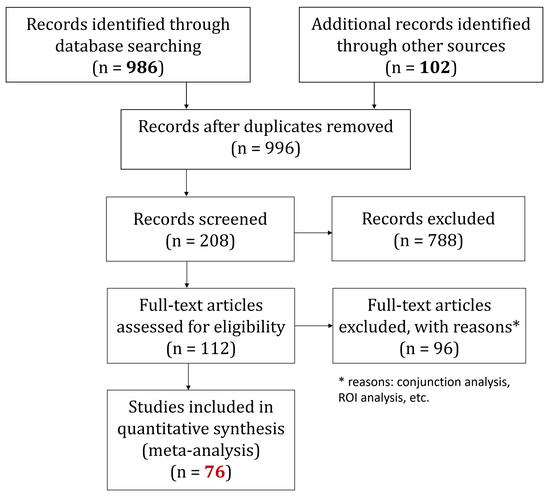
- Deductive reasoning is a process to draw definitive conclusion, whereas inductive reasoning is a process to find underlying relations from given information.
- Neuroscientists hardly tackled both types of reasoning simultaneously, instead, they usually investigated brain regions essential to each reasoning type separately, if any, with a few exceptions.
- Therefore, we will perform meta-analysis, combining the two processes.

The necessity of developing advanced meta-analysis

- Conventional Meta-Analysis tools (e.g., ALE, MKDA) lack generalizability.
- Newly-developed Bayesian Meta-Analysis tools require substantial amount of computing resources.
- We aimed to develop computationally-efficient generative model that could produce generalized maps for both reasoning processes.

Systematic Selection of the Studies

Term: (Reasoning) AND (Transitive Inference)
Database: Pubmed
Publication Date: ~ 2019/12/31



Preprocessing

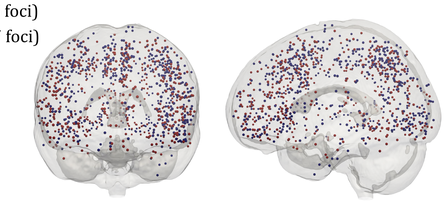
Included Contrasts (215 maps)

Inductive (95 maps)
- Inductive
- Inductive - Baseline
- Inductive - Deductive
- Inductive - Inductive
- Inductive (Parametric)
- Inductive (Interaction)

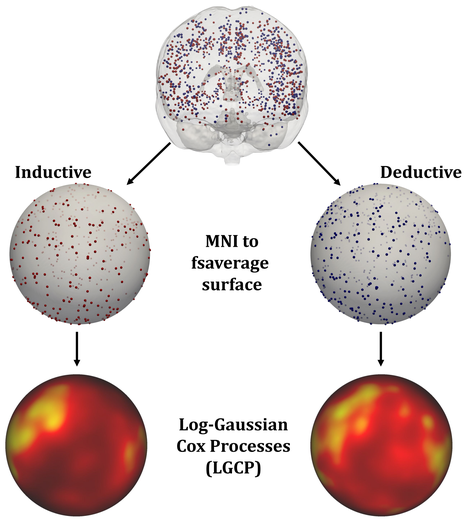
Deductive (120 maps)
- Deductive
- Deductive - Baseline
- Deductive - Inductive
- Deductive - Deductive
- Deductive (Parametric)
- Deductive (Interaction)

Included Coordinates (1413 foci) rendered on the brain

- **Inductive** (666 foci)
- **Deductive**(747 foci)



Bayesian Meta-Analysis on the Cortical Surface (BMACS)



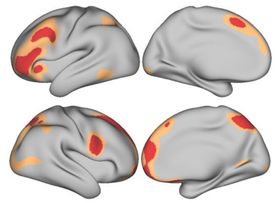
Bayesian Meta-Analysis on the Cortical Surface (BMACS)

- A Cox Process is a spatial point process which generates point patterns, assuming spatially varying random effects.
- A Log-Gaussian Cox Process (LGCP) is one of the of Cox processes where log intensity follows a Gaussian Process.
- We adopted LGCP to estimate the underlying maps for each reasoning process.
- Through this, we could achieve efficient and reliable estimation.
- Since our main interest is the activation patterns on the cortex, we focused on estimating maps on the cortical surface.

Results

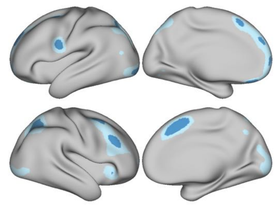
Regions related to each reasoning process

- **Inductive Reasoning**



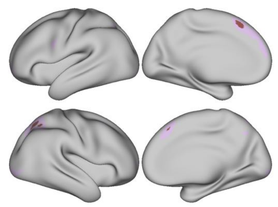
- The map shows exceedance probability greater than 50% or 95% that intensity is greater than 1.
- Core regions are left 47, 8B, 8Av, right 6, 7, OFC, 9/10, MIP.

- **Deductive Reasoning**



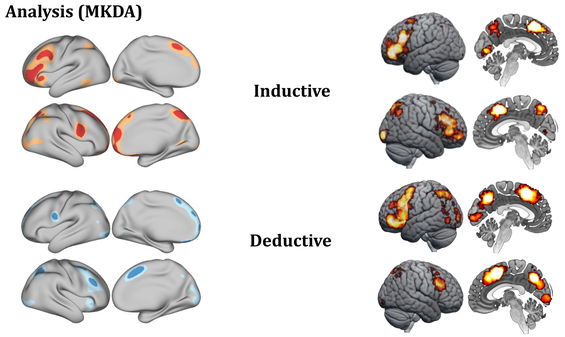
- The map shows exceedance probability greater than 50% or 95% that intensity is greater than 1.
- Core regions are left 9, 10, OFC, 8B, right 8B, 8Av, 40.

Common regions activated through two reasoning processes



- The map shows conjunction of the two reasoning maps.
- Commonly activated regions are left/right 8B, MIP, V1/V2.
- There are not so many regions shared by the two reasoning processes.

Similar patterns between BMACS and Multi-level Kernel Density Analysis (MKDA)



Subcortical Areas that are not included in the BMACS

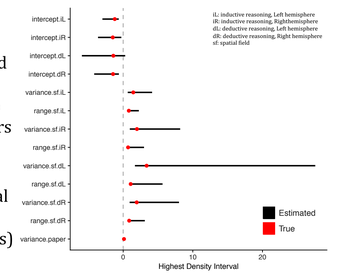
- Most of the coordinates are reported in the Caudate Nucleus, Pallidum, Putamen and Thalamus.
- These regions have been reported in relation to high-level human cognition.

	Left	Right
Accumbens	3	8
Amygdala	2	4
Caudate	35	31
Hippocampus	8	12
Pallidum	32	28
Putamen	27	32
Thalamus	46	34

Validation

Simulation

- We simulated a dataset based on the mean estimated values from BMACS and re-estimated the parameters to show that our model recovers the true values.
- The estimated values with 95% Highest Density Interval (black line) successfully re-covered true values (red dots)



Classification Accuracy

- Balanced accuracy of BMACS is 0.8205.
- Balanced accuracy of MKDA + Naive Bayes Classifier (NBC) is 0.5916.
- BMACS shows better performance compared to MKDA + NBC.

BMACS

	Inductive	Deductive
Inductive	0.8718	0.1282
Deductive	0.2308	0.7692

MKDA + NBC (control)

	Inductive	Deductive
Inductive	0.4105	0.5895
Deductive	0.2273	0.7727

Conclusion

- We have successfully developed and validated a novel generative meta-analysis model on the cortical surface (BMACS).
- Using BMACS, we could infer generative maps for inductive and deductive reasoning processes and discriminate regions that are specific to each process.
- BMACS outperformed predicting each type of reasoning in terms of classification accuracy.
- Future study should investigate the subcortical areas using another method corresponding to BMACS.

We developed a novel meta-analysis tool on the cortical surface, called Bayesian Meta-Analysis on the Cortical- Surface (**BMACS**).
Using BMACS, we could study thoroughly the common and different activation patterns involved in inductive and deductive reasoning.