Large-scale brain networks underlying domain-specific memory, intelligence, and academic performance

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Poster M732

Neuroinformatics and Brain Connectivity Lab

Introduction

Academic performance is believed to rely, in part, on intelligence. This phenomena has been studied at length, but findings concerning the neural substrates of intelligence in intrinsic brain organization have been mixed, and little attention has been paid to how the relationships between intelligence and brain organization vary between sexes.

Here, we investigate the role of IQ in domain-specific learning in a historically male-dominated domain. We further probe how the intrinsic organization of large-scale brain networks reflects IQ and its role in learning, and how this relationship differs with respect to biological sex.

Methods

Participants

- 107 RH undergraduate students (48 female)
- No history of neurological/psychiatric diagnosis
- Enrolled in first calculus-based physics course (two course types: active learning instruction & traditional lecture)

Data collection

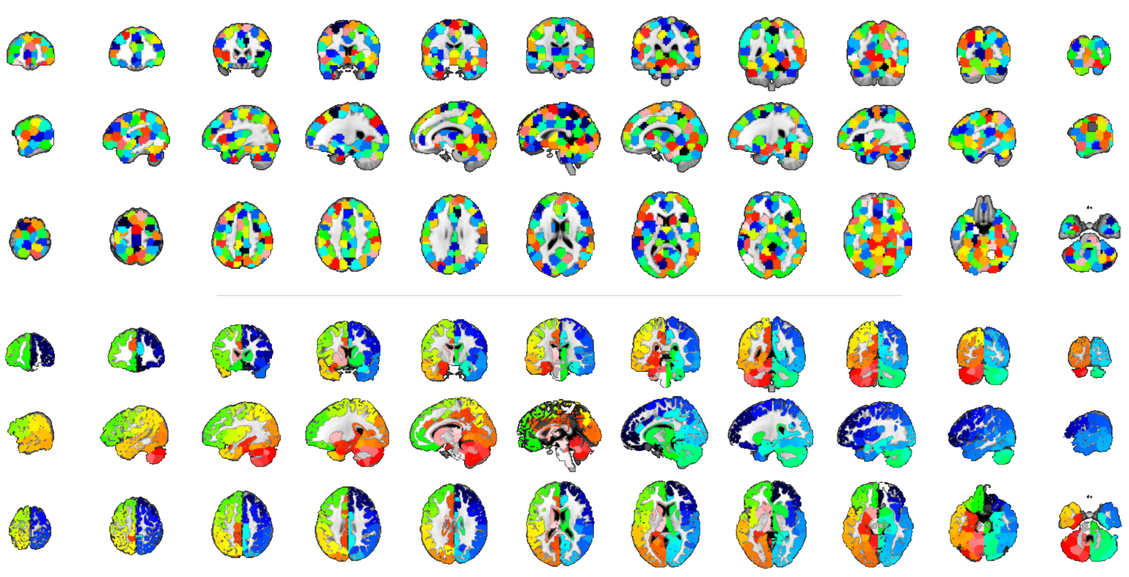
- All data were collected both pre- and post-instruction
- Behavioral data
  - IQ (WAIS-IV)
  - Grade in the physics course
  - Accuracy during tasks in the scanner
- MRI data
  - T1-weighted structural images
  - Resting-state functional MRI (fMRI; 12 minutes)
  - Retrieval task (physics, general)
  - Physics reasoning task (Force Concept Inventory; FCI)
  - Transitive inference task

Data analysis

- Preprocessed to mitigate head motion, low-frequency drift, aligned to MNI template
- BOLD signals were extracted, per region, using data-driven, functional brain parcellations (Fig. 1) and correlated, pairwise for connectivity matrices
- Efficiency, modularity, and path length calculated using bctpy for each subject, task, condition, session
- Paired t-tests for change in IQ scores pre- to post-instruction
- OLS regression: pre, post, change in IQ & class type, controlling for age, year in uni.
- OLS regression: pre, post, change in IQ & area under the curve of topological metrics, controlling for head size, average FD, year in uni., age
- Corrected for multiple comparisons under dependence (Li & Ji, 2005; Šidák, 1967)

Figure 1. Parcellations used for assembly of brain graphs

All topological measures were calculated twice, once for each parcellation, to verify that our results hold across network definitions. Both the Craddock (2012; above) and Finn/Shen (2015; below) are functionally defined, with 270 and 268 regions, respectively.



IQ significantly increases over the course of a physics class

- Although IQ is assumed to be stable, full-scale IQ (FSIQ) scores in both male and female students significantly increase over the course of the class (t_{male} = 11.3, t_{female} = 7.8, $p < 0.001$)
- Only Perceptual Reasoning (PRIQ; t_{male} = 3.7, t_{female} = 2.3) & Processing Speed (t_{male} = 4.6, t_{female} = 4.3) subscores significantly increased ($p < 0.001$)
- No significant differences in changes in IQ score between male and female students

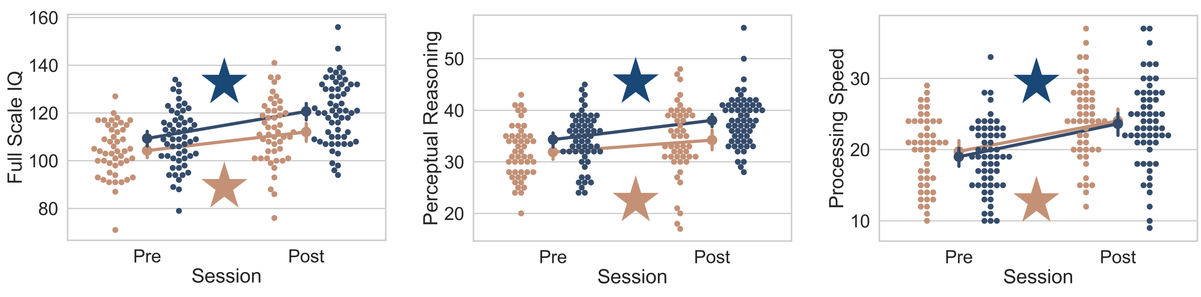


Figure 2. Change in IQ scores pre- to post-instruction

Male and female students' changes in Full Scale IQ and it s subscores across the course of the semester.

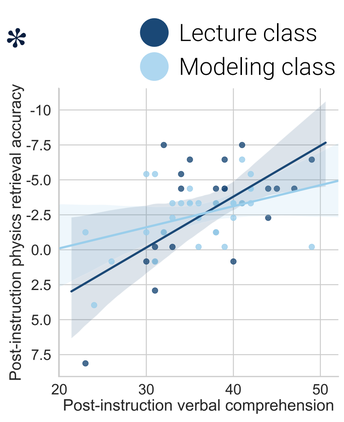
- Only full-scale IQ increases in male students were related to course type (modeling/lecture), when controlling for age and number of years at university (F = 4.083, $p(F)$ = 0.0113)

*IQ neither predicts nor reflects learning in a physics class**

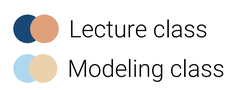
- Neither pre-instruction nor changes in IQ scores were related to course grades or changes in task accuracy
- **Post-instruction Verbal Comprehension** is associated with **post-instruction physics retrieval accuracy** in male students ($p < 0.01$), after controlling for age, years at university, and class type.

Figure 3. Verbal comprehension & physics retrieval accuracy in male students

Male students' changes in Full Scale IQ and its subscores across the course of the semester, in lecture and modeling classes.

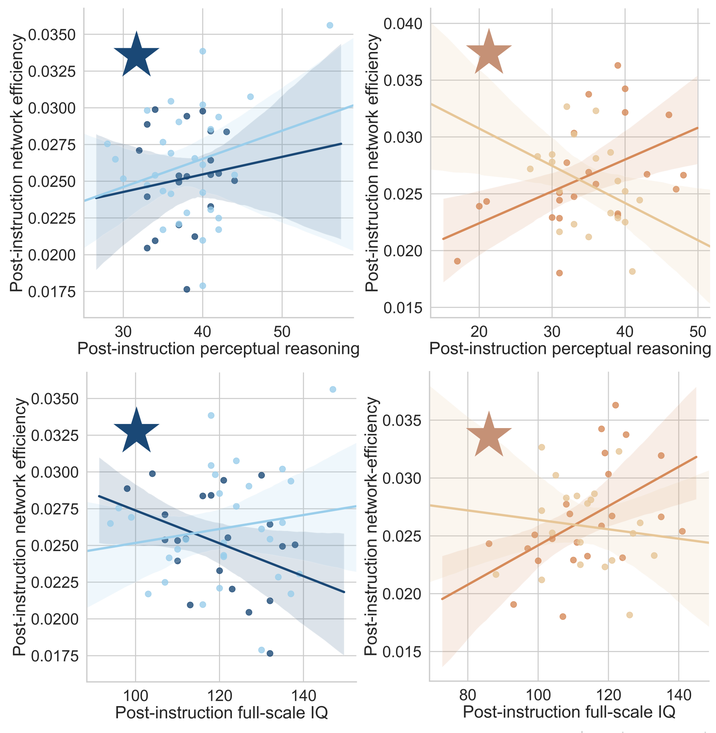


IQ is differentially related to brain network organization with respect to class type & sex



Resting-state

No significant relationships between resting-state brain network organization and IQ.



Physics Retrieval

Post-instruction characteristic path length and **efficiency** are related to **post-instruction PRIQ and FSIQ** (Fig. 4: efficiency shown, relationship is the same for path length), but the direction of these relationships is **different for female and male students**, and depending on **class type** in which they were enrolled.

No trends in general retrieval.

Figure 4. Perceptual reasoning (top), full IQ (bottom) and efficiency during physics retrieval in male and female students

PRIQ (top) and FSIQ (bottom) are significantly related to network efficiency and characteristic path length (not shown), with significant interactions between IQ, sex, and class type (modeling vs. lecture)

Force Concept Inventory

Post-instruction network efficiency, characteristic path length during **physics reasoning** in the FCI task was also significantly **related to post-instruction PRIQ and FSIQ** (Fig. 5).

- Direction of IQ-brain relationship **depends on sex and class**
- **Topology differs between the sexes and classes**, too, differently per class and sex.

Post-instruction network topology is also related to **changes in both PRIQ and FSIQ** over the course of the semester (in the same directions seen in Fig. 5)

- Direction of **IQ-brain relationship depends on sex and class**
- **No relationship between sex, class, or sexXclass and topology.**

No such trends seen in control condition.

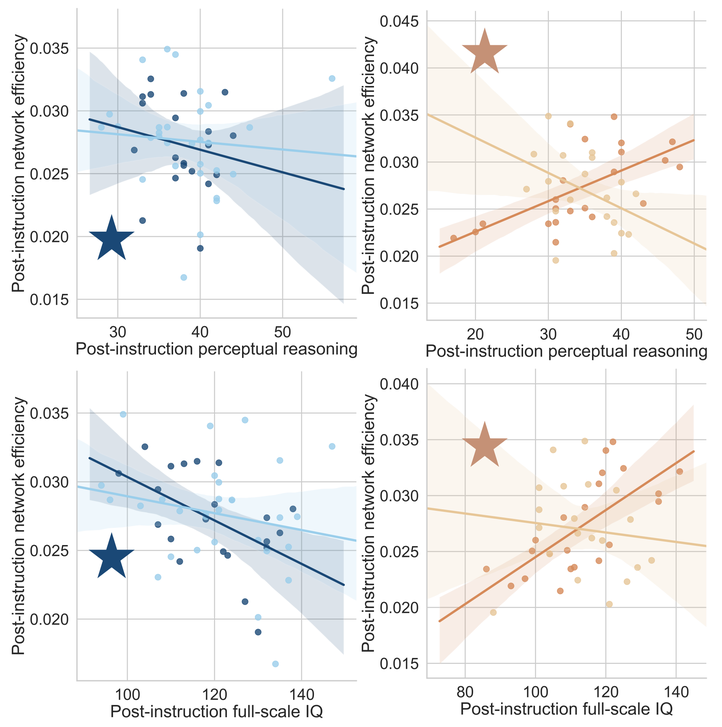


Figure 5. Perceptual reasoning, full IQ and efficiency during physics reasoning in male and female students

PRIQ (top) and FSIQ (bottom) are significantly related to network efficiency and characteristic path length (not shown), with significant interactions between IQ, sex, and class type (modeling vs. lecture)

Transitive Inference

Changes in network topology over the course of the semester were significantly related to **pre-instruction working memory scores** (Fig. 6). Pre-instruction topology during the control condition is significantly related to verbal comprehension and this relationship differs with sex and class type, too.

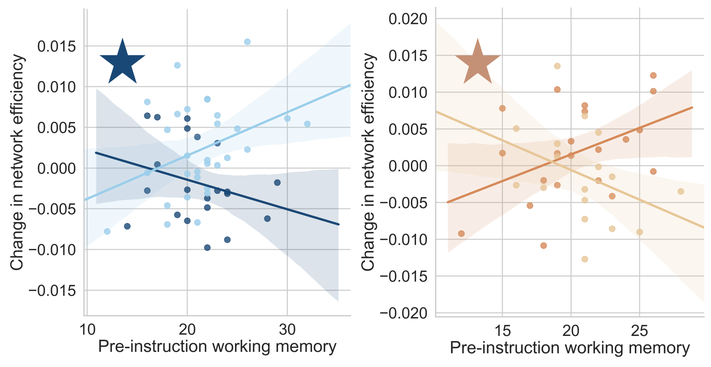


Figure 6. Working memory and efficiency during general reasoning in male and female students

WMIQ significantly related to network efficiency and characteristic path length (not shown), with significant interactions between IQ, sex, and class type (modeling vs. lecture)

Conclusions

- IQ significantly increases over the course of a semester of calculus-based physics, driven by increases in perceptual reasoning and processing speed, for all students.
- IQ is unrelated to outcomes measures, making it a poor predictor of success in a physics course, with one exception: post-instruction verbal comprehension predicts post FCI accuracy.
- Perceptual reasoning and full-scale IQ are related to brain network topology during physics-related tasks post-instruction and these relationships differ based on sex and course type.
- Task-based topology is more related to IQ than resting-state, modularity was not related to IQ.

References

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Funding

This work was funded in part by the National Science Foundation (NSF REAL DRL-1420627).

Code available on GitHub