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

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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 undergraduate students (48 female, all right-handed)
- No history of neurological or psychiatric diagnosis
- Haven't taken a calculus-based physics class before study

Data collection (acquired pre- and post-instruction)

- Behavioral data included
  - IQ (WAIS-IV)
  - Grade in the physics course
  - Accuracy during tasks performed in the scanner
- MRI data included:
  - T1-weighted structural images
  - Resting-state functional MRI (fMRI; 12 minutes)

Data analysis

- Preprocessed to mitigate head motion, low-frequency drift, aligned to MNI template
- Regionwise signals were extracted using data-driven, functional brain parcellation (Figure 1) and correlated, pairwise for connectivity matrices
- Calculated efficiency, modularity, and path length
- Paired *t*-tests for change in IQ scores pre- to post-instruction
- IQ correlated with on each graph measure pre- and post-instruction, and the change from pre- to post-instruction

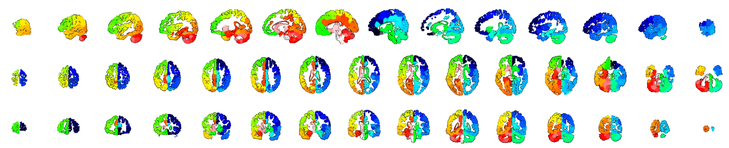


Figure 1. Functional brain parcellation per Finn et al. (2015)

Finn and colleagues performed data-driven clustering on functional MRI data to yield 268 distinct functional regions across the cortex and subcortex.

Finn, E. S., Shen, X., Scheinost, D., Rosenberg, M. D., Huang, J., Chun, M. M., ... Constable, R. T. (2015). Functional connectome fingerprinting: identifying individuals using patterns of brain connectivity. Nature Neuroscience, 18, 1664.

IQ significantly increases over the course of the physics class

- IQ scores in both male and female students significantly increased over the course of the class: $t_{male} = 11.3$, $t_{female} = 7.8$, $p < 0.001$
- Only Perceptual Reasoning ($t_{male} = 3.7$, $t_{female} = 2.3$) & Processing Speed ($t_{male} = 4.6$, $t_{female} = 4.3$) subscores significantly increased ($p < 0.001$)
- There were no significant differences in changes in IQ score between male and female students

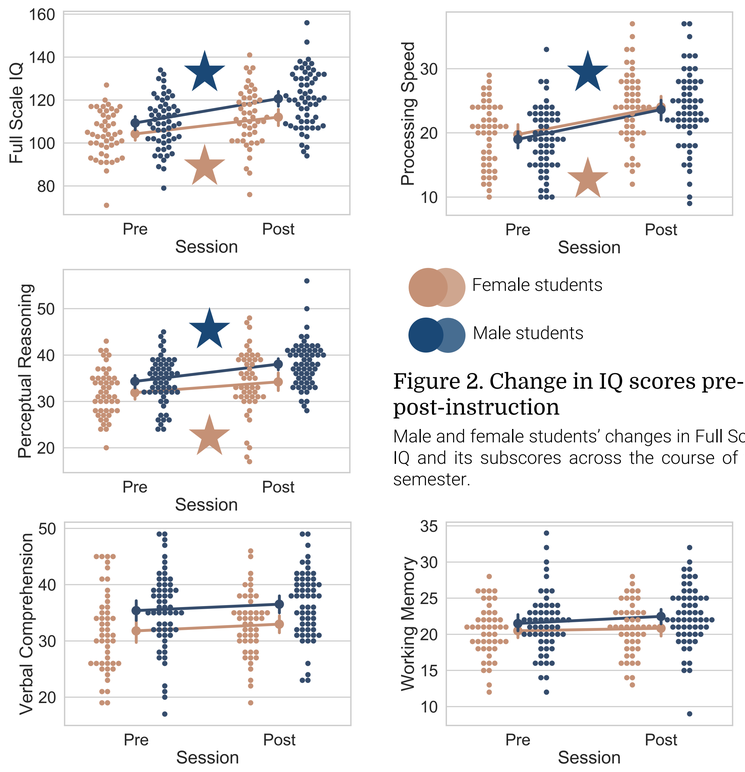


Figure 2. Change in IQ scores pre- to post-instruction

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

IQ neither predicts nor reflects learning in a physics class*

- Pre-instruction IQ scores were not correlated with course grades or changes in task accuracy
- Pre- to post-instruction changes in IQ scores were not correlated with course grades or changes in task accuracy
- Changes in Perceptual Reasoning is associated with course grade in female students ($p < 0.01$)

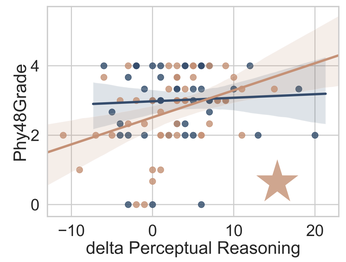


Figure 3. Perceptual Reasoning & grade

IQ is differentially related to intrinsic brain network organization

- Full scale IQ is related to characteristic path lengh in female students pre-instruction, but not post-instruction ($p < 0.05$; Figure 4)
- There are no relationships between IQ and intrinsic global brain organization in male students pre- or post-instruction
- Pre-instruction IQ does not predict change in brain organization
- Post-instruction Working Memory scores are significantly associated with change in intrinsic brain organization in female students ($p < 0.05$; Figure 5)

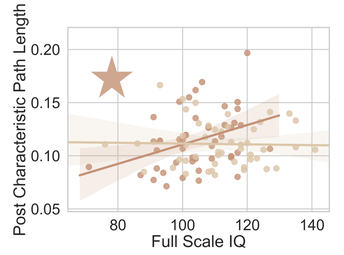
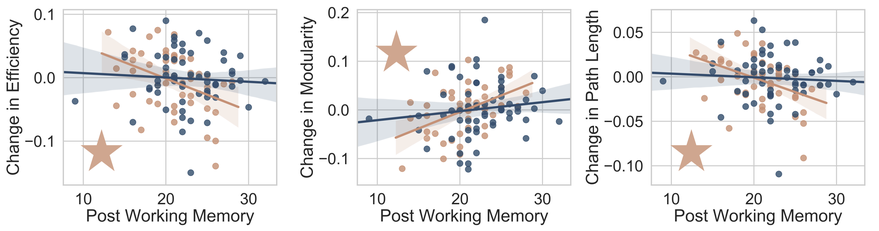


Figure 4. IQ and path length in female students

Pre-instruction, full Scale IQ is related to characteristic path length (dark gold), but this relationship disappears post-instruction (light gold)

Figure 5. Working Memory and brain organization

Changes in brain organization (global efficiency, modularity, and path length are reflected by Working Memory scores post-instruction in female students



Conclusions & future directions

- There were significant gains in IQ over the course of male and female students' first physics class, but no sex differences therein
- Gains in IQ were driven by gains in two subscores: Processing Speed and Perceptual Reasoning, are these skills important for learning physics?
- IQ is a poor predictor of performance in a physics class
- Only changes in Perceptual Reasoning over the course of the class in female students were related to course outcomes
  - Sex differences in mental rotation are supported by a wealth of research
  - Do female students' increase in perceptual reasoning minimize these differences?
- These significant IQ subscores were not reflected by intrinsic brain organization
  - Are they related, instead, to task-evoked brain organlization?
  - Greene et al. (2018) found that task-evoked brain networks better IQ
- Does intrinsic brain organization change during a physics class to better support working memory processes?

Greene, A. S., Gao, S., Scheinost, D., & Constable, R. T. (2018). Task-induced brain state manipulation improves prediction of individual traits. Nature Communications, 9(1), 2807. https://doi.org/10.1038/s41467-018-04920-3

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