Understanding the Neural Substrates of Physics Problem Solving: Brain Mechanisms and Behavior Correlates

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Introduction

- Education research examines student problem solving to facilitate learning; and functional magnetic resonance imaging (fMRI) can be used to measure those neural processes.
- Neuroeducation research seeks to bridge understanding of brain function with effective teaching practices in Science Technology Engineering and Mathematics (STEM) [1,2].
- The neural correlates and network dynamics of physics problem solving have not been well characterized, and relationships between behavioral measures and physics problem solving related brain function remain unknown.
- Visuospatial skills are known to positively associate with physics problem solving ability [3], but a gender achievement gap in physics performance persists and remains unexplained [4].
- We used fMRI to delineate brain activity and network dynamics across physics problem solving processes, and probed behavioral correlates for gender differences.

Methods

Data collection

- fMRI data: 80 healthy right-handed participants (40 female; 18-25 yrs) on a 3T GE 750W scanner.
- Participants: FIU undergraduates, first-time enrollees in 13-week calculus-based college physics.
- Methodology: Pre-instruction WAIS IQ testing followed by post-instruction fMRI.
- Problem-Solving Task: Students solved problems based on the Force Concept Inventory (FCI; **Fig 1a**) [5] assessment of physics conceptual reasoning. The FCI task was contrasted with high-level reading comprehension control questions (**Fig 1b**).

Data processing

- Analyses performed in FSL [6], activation maps thresholded at $P_{FWE\ corrected}$ <0.05 (voxel-level threshold z>3.09).
- FCI > Control assessed for full FCI questions and for each of the three FCI screens separately. Two group t-test identified gender differences. The resulting ROI was probed to examine correlations with cognitive skills as measured by WAIS subtests.

Results

- FCI all screens: Fronto-temporo-parietal activity in bilateral superior and middle frontal gyrus, inferior posterior parietal cortex, and bilateral middle to inferior temporal gyri (**Fig 2**).
- FCI dynamics: Initial Screen 1 (S1) fronto-temporo-parietal activation shifted to parietal Screen 2 (S2) emphasis followed by Screen 3 (S3) default mode engagement (**Fig 3).**
- Male students outperformed female students on the FCI after physics instruction (**Fig 3**). High WAIS Symbol Search performance was linked to increased physics problem solving related activity in left supramarginal gyrus for male but not female students (**Fig 4**).

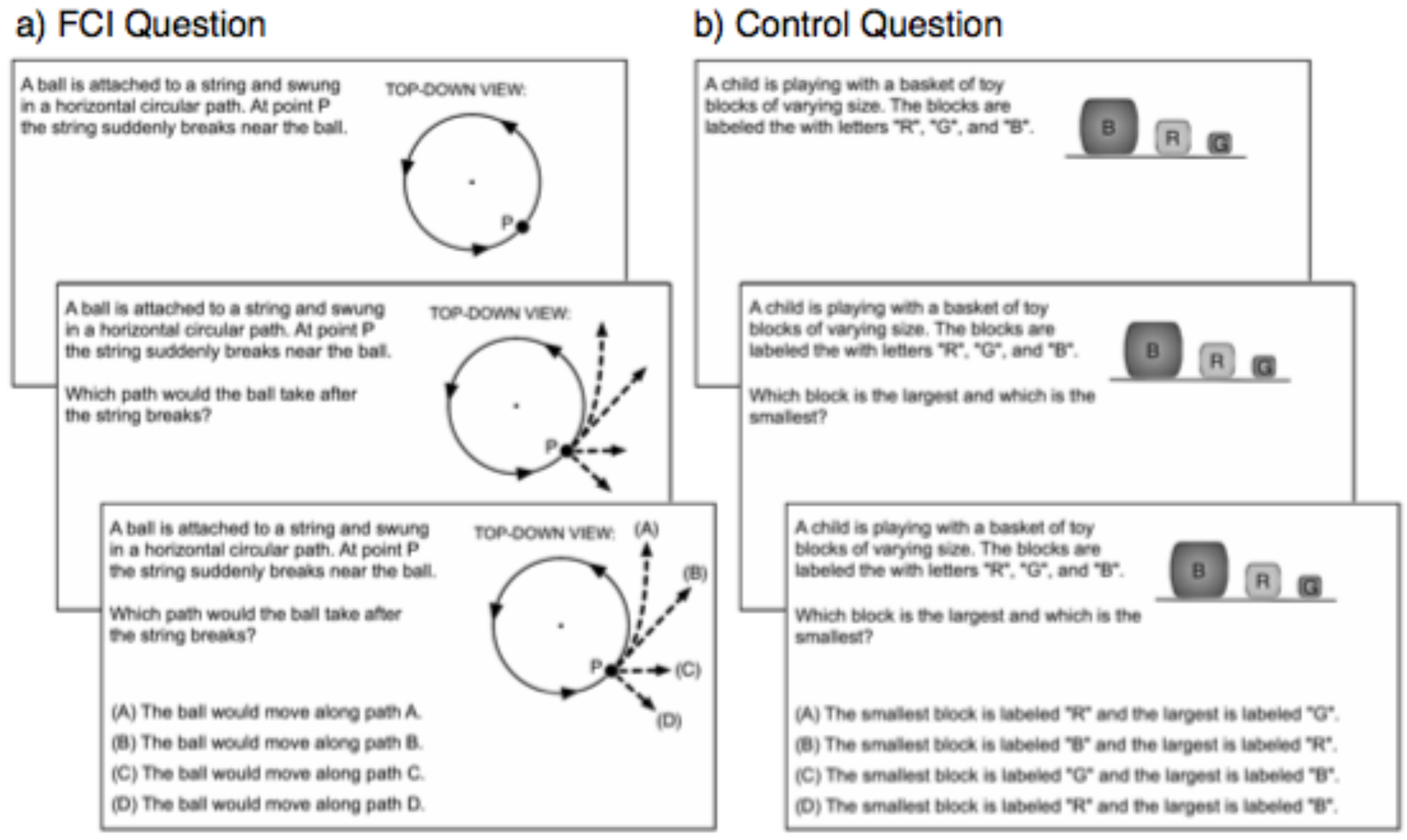


Figure 1 (above). fMRI Paradigm and Baseline Control. a) Three-screen sequential progression of an example in-scanner FCI question. Screen 1 (S1) consisted of text and picture descriptions of a physical scene, Screen 2 (S2) posed a physics question, and Screen 3 (S3) listed possible answer choices b) Example high-level control question, designed to be structurally similar to the FCI but to not involve physics reasoning.

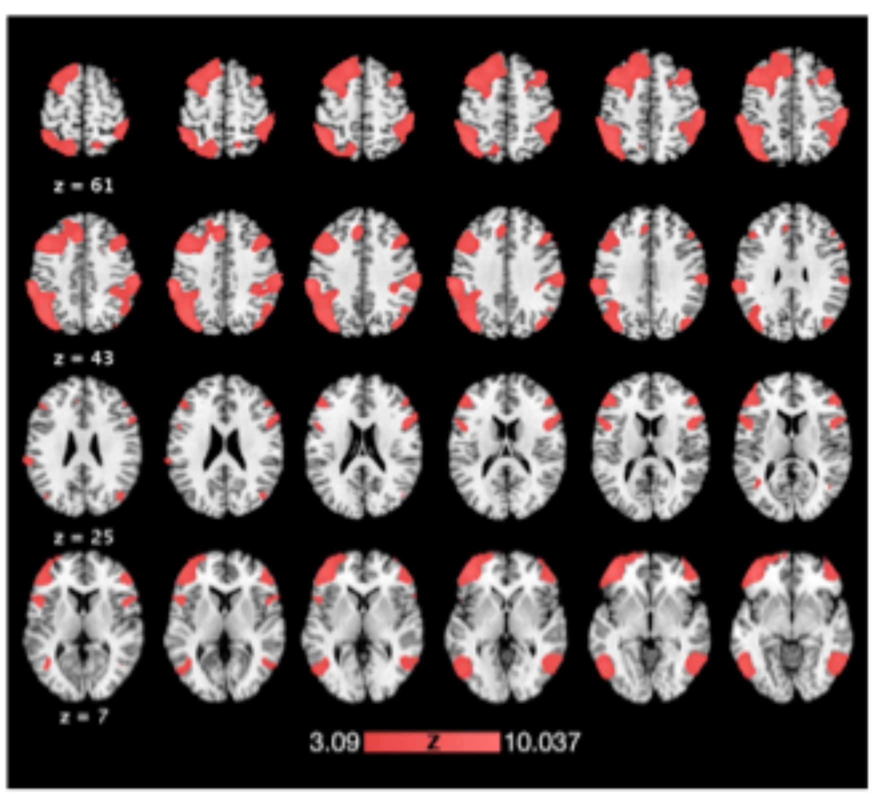


Figure 2 (left). Physics Problem Solving: fMRI Results. Activation of FCI > Control after students received university physics instruction. All FCI screens are included in these results.

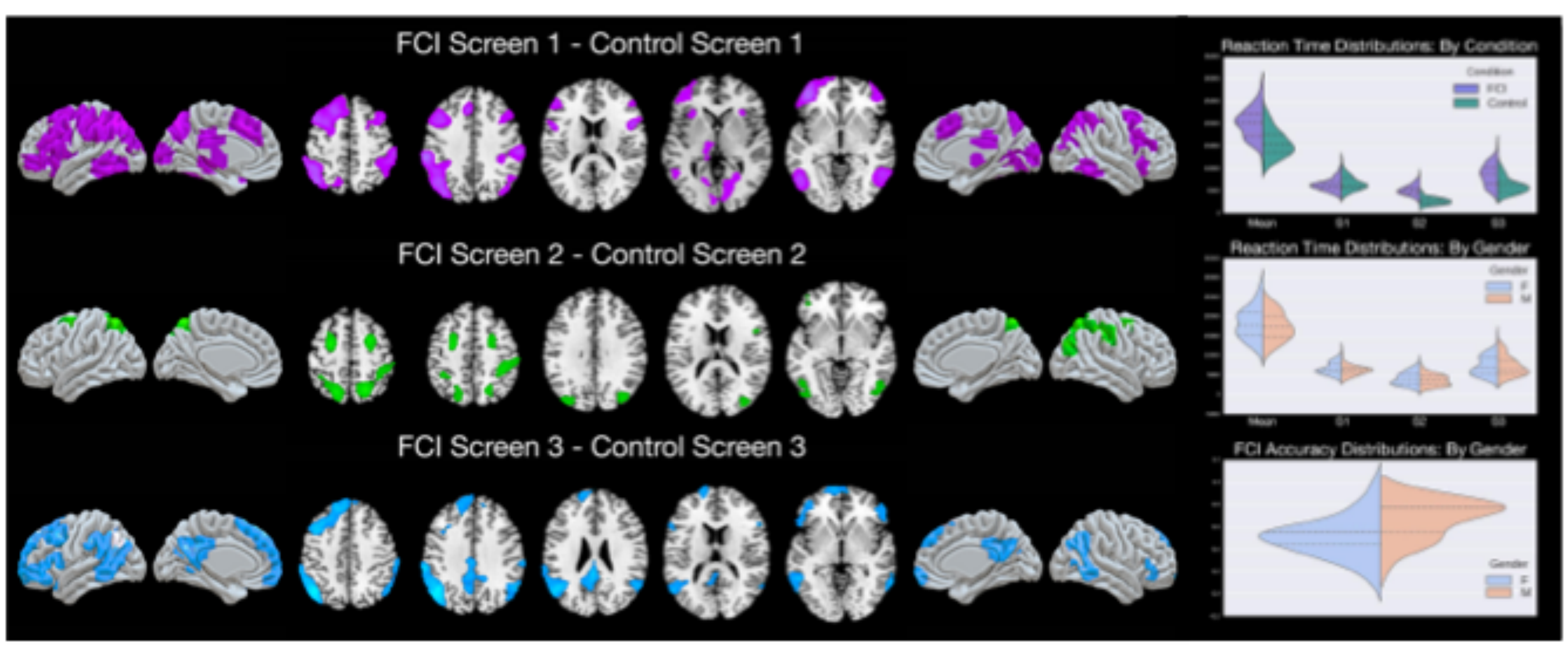
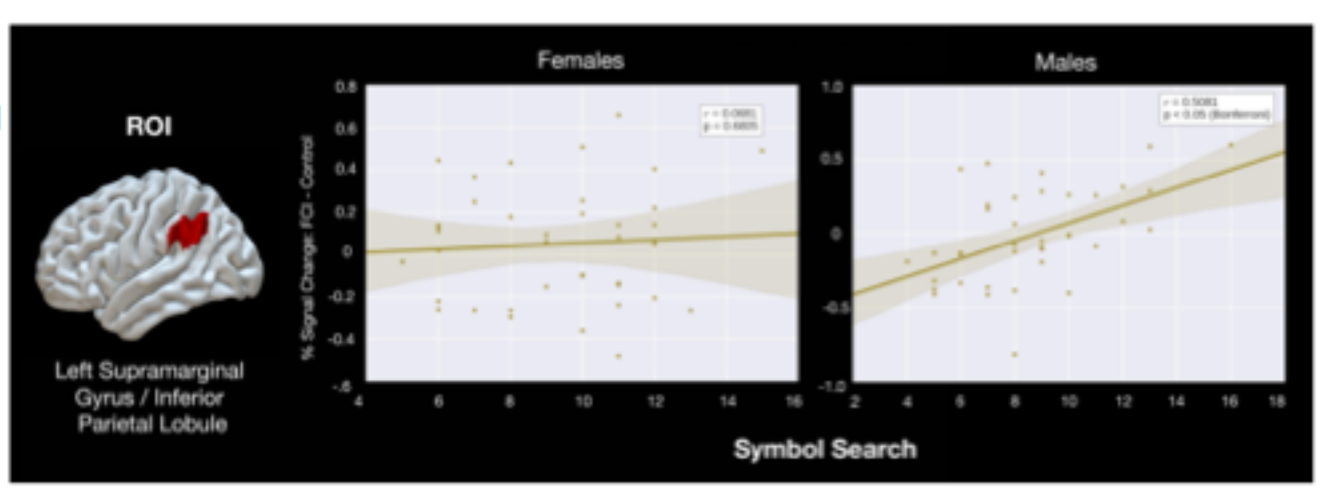


Figure 3. Physics Problem Solving Dynamic Brain Activity: fMRI and Behavioral Results. fMRI activation of FCI > Control is shown for each of three successive screens. Reaction time and accuracy distributions are shown to the right across screens and genders.

Figure 4. Gender differences and behavior correlates. Left supramargional gyrus showed increased problem solving related activity in males vs. females. Correlations by gender are shown between symbol search test and ROI engagement in problem solving. Males with increased visuospatial processing skills had increased ROI activity.



Discussion

- First time observations of physics problem solving brain activity: executive control network (ECN) cooperation with salience network, temporal integration shows importance of language and memory processes in physics problem solving [7].
- Brain dynamics: ECN, salience, and temporal nodes in S1 may detect semantic conflicts in text [7], transient S2 parietal and frontal eye field activity may guide visuospatial focus [8,9], and S3 default mode and ECN cooperation indicates autobiographic-based reasoning [10].
- Gender gap insights: symbol search tests visuospatial processing speed, supramarginal gyrus discriminates between spatial cues [11]. Increased region of interest (ROI) activity associated with visuospatial skills for male but not female students may indicate effective visual feature identification supports physics problem solving success differently across genders.

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