The Neuroscience of Science Education

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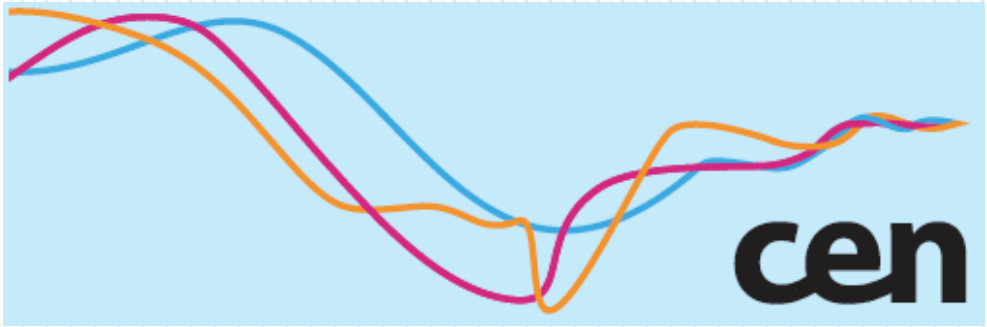


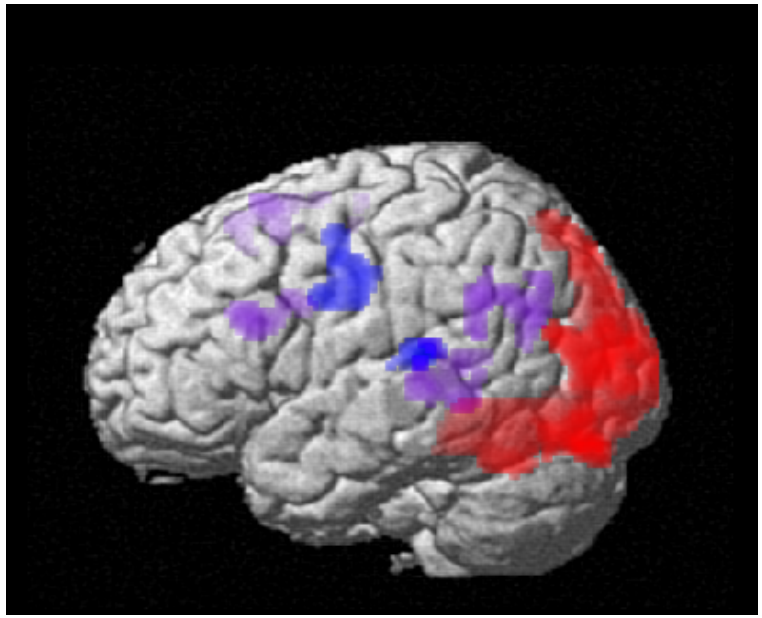
What is Scientific Reasoning?

- Mental activities that are involved when individuals attempt to make discoveries about the world
- Domain general cognitive processes that are used to help formulate hypotheses, design experiments, collect data (or make observations), and evaluate evidence
- Same cognitive operations that humans use in many non-scientific domains, such as causal reasoning, deductive reasoning, analogical reasoning, hypothesis testing, and problem solving
- I will focus the majority of this presentation on the use of causal reasoning, deductive reasoning and analogical reasoning in scientific thinking

Exploring Reasoning in the Brain

Functional imaging (e.g. fMRI)
measures "current processing"
within an individual

Structural images appear to reflect:
"learning" "ability" possibly "potential"
differences ***across individuals***



Exploring Reasoning in the Brain

- Almost all work carried out with adolescents and young adults

- Difficulties of working with children include noise, motion artefacts, lack of structural templates.

- Lowest ages typically 6 years of age

Three Examples....

- **Causal inference**

Increased atmospheric CO2 output causes global warming

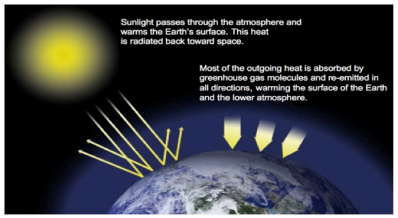


Figure 1 (source: http://climate.nasa.gov/causes)

- **Deductive inference**

E.g., all mammals have fur. Wombats are mammals, therefore wombats have fur

- **Analogical inference**

E.g., Rutherford Atom ⇔ Solar System

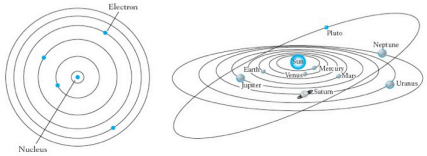


Figure 5 (Source: Galotti, Fernandes, Fugelsang, & Stolz, 2010; *Nelson Publishing*)

Causal Inference in the Brain

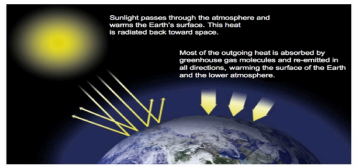


Figure 1 (source: http://climate.nasa.gov/causes)

- Perception is different from reasoning
- Different systems underlie causal perception from causal reasoning

- Evidence from Split Brain patients (callosotomy surgery)
- Left hemisphere involved in causal inference, right hemisphere involved in causal perception (Roser et al., 2005)

Causal Inference in the Brain

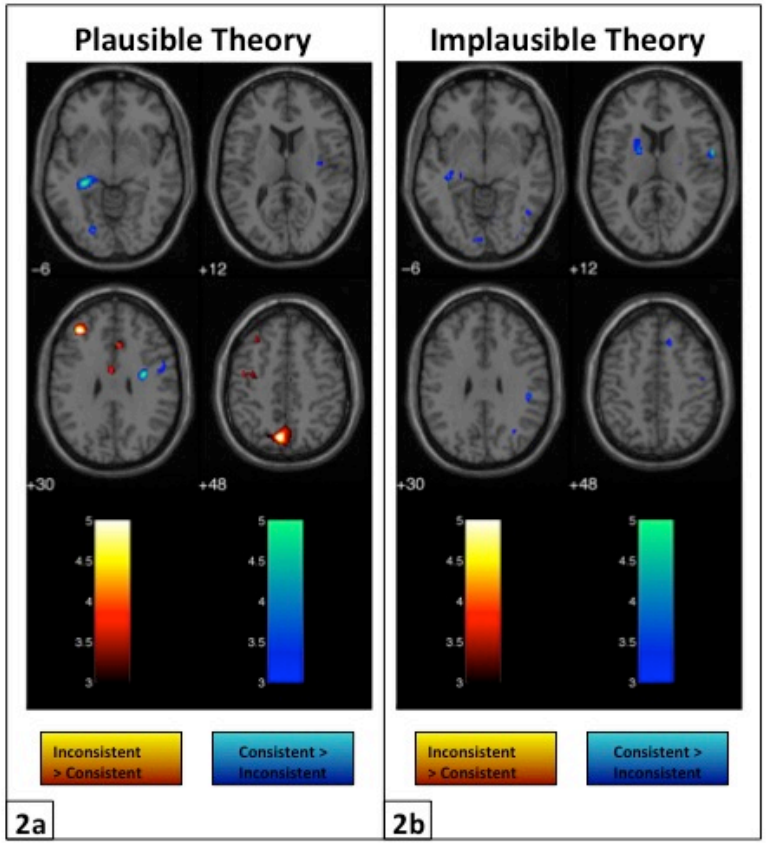
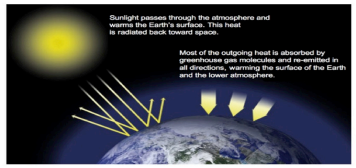


Figure 2 (Source: Fugelsang & Dunbar, 2005; *Neuropsychologia*)



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Consistency with prior beliefs is a key modulating factor!

Causal Inference in the Brain

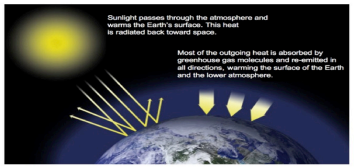


Figure 1 (source: http://climate.nasa.gov/causes)

- Evaluating causal explanations recruited :

(1) parts of the parahippocampal cortex (associated with semantic knowledge) when the explanation was consistent with prior beliefs

(2) the DLFPC (Dorsal Lateral Prefrontal Cortex) and Anterior Cingulate (AC) when hypothesis was inconsistent with prior beliefs

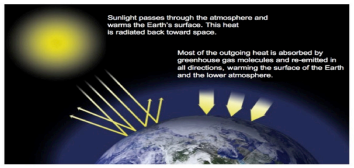
(Fugelsang & Dunbar, 2005; Parris et al., 2009)

Deductive Inference in the Brain

- Imaging suggests that both language-based and visual spatial modes are engaged during deductive reasoning (Goel, 2007, 2003)
- Posterior to anterior shift with age/expertise (Houde et al. 2001)
- A fractionated system that can be dynamically reconfigured in response to the familiarity of the task

- LPFC activation increases when level of belief conflict increases
- Implication of DLPFC (Dorsal Lateral Prefrontal Cortex) … especially in tasks involving the integration of prior knowledge

Deductive Inference in the Brain



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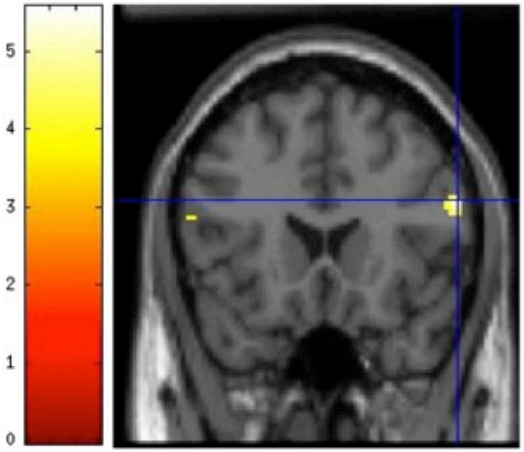


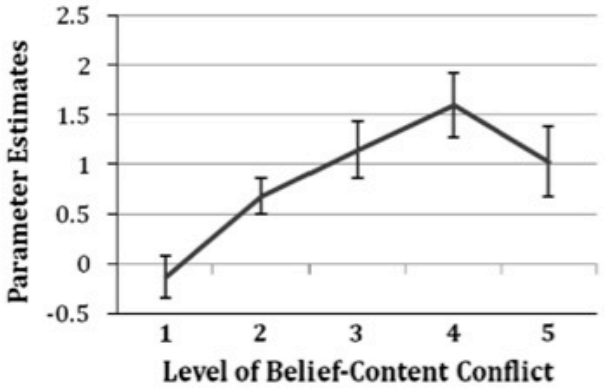


Figure 4 (Source: Stollstorf, Vartanian, & Goel, 2012; *Brain Research*)

LPFC activation increases when level of belief conflict increases

Analogical Inference in the Brain

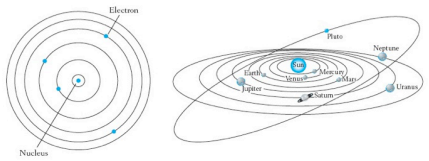


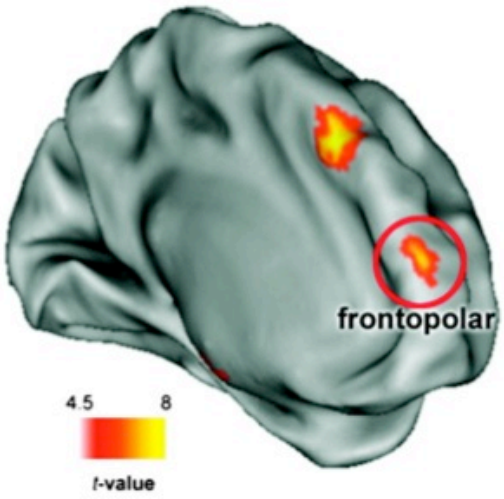
Figure 5 (Source: Galotti, Fernandes, Fugelsang, & Stolz, 2010; *Nelson Publishing*)

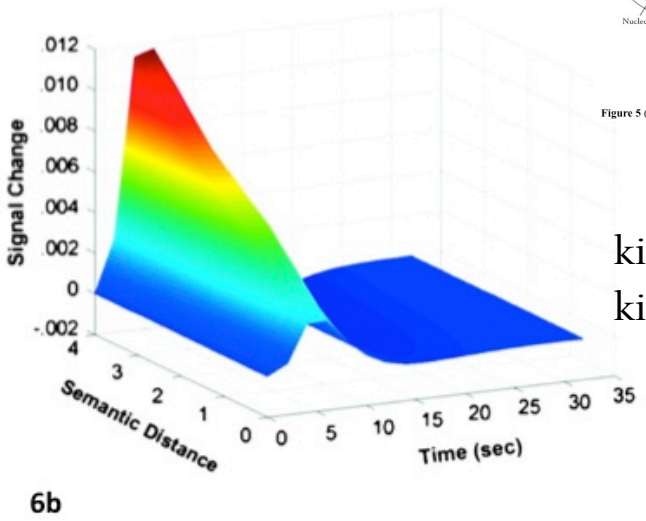
- Some studies with children from age 8 years.
- Multiple PFC regions implicated
- Need to differentiate perceptual from verbal analogies
- Evaluating or producing analogies revealed that:

(1) Frontopolar cortex (part of the PFC) and right lateral PFC are sensitive to integration of multiple systems of visual relations (either abstract or concrete; Raven's MAtrices)

(2) Frontopolar cortex and aLiPFC involved in semantic similarity judgments

Analogical Inference in the Brain





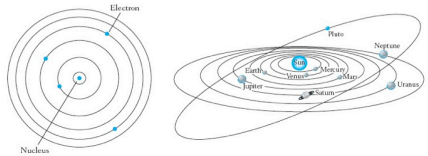


Figure 5 (Source: Galotti, Fernandes, Fugelsang, & Stolz, 2010; *Nelson Publishing*)

kitten:cat::spark:fire
kitten:cat::puppy:dog

Figure 6 (Source: Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; *Cerebral Cortex*)

Semantic distance modulates brain activity
(perhaps non relational systems involved with low semantic distance (Leech et al. 2008)

Analogical Inference in the Brain

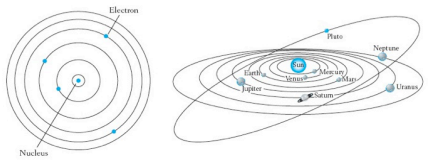


Figure 5 (Source: Galotti, Fernandes, Fugelsang, & Stolz, 2010; *Nelson Publishing*)

- Some studies with children from age 6 years.
- 6- to 13-year-olds engage similar systems but do so too late to influence response (Wright et al, 2008)
- 8- to 12-year-olds did not engage RLPFC when more than 2 relations needed to be integrated (Crone et al., 2009)

The Key ideas...

- Findings are consistent with the idea that executive functions can be dissociated into *Evaluative* and *Executive* components involving the AC and DLPFC respectively
- AC identifies conflict and DLPFC resolves conflict
- Few developmental fMRI studies
- BUT findings are consistent with the suggestion of the importance of conflict monitoring in classic theories of reasoning (e.g., Piaget's reflective abstraction)

General Lessons from Neuroimaging…

- Fractionated generalist systems made from basic cognitive building blocks
- Both executive control and semantic knowledge systems play an important role in scientific reasoning
- Reasoning that is consistent with prior knowledge recruits different a neural system than reasoning that is inconsistent with prior knowledge
- The late maturing of the DLPFC may partially underlie prolonged development of reasoning skills

Putative Implications for Education

- Participants engage different reasoning systems when presented with hypotheses consistent or inconsistent with prior beliefs or knowledge

(1) So… increasing domain knowledge (evidence) should be a pre-cursor to teaching inferential techniques (e.g., hypothesis testing)

(2) Improving "conflict monitoring" will have knock-on effects on reasoning in the brain

More developmental research needed!

Thank you for your attention!