Cognitive variability and developmental disorders
Insights from research on the mechanisms of learning

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Integrating levels

Dialogue

Neuroscience

Psychology

Education
The interface of brain and cognition

- Example: conditions that activate left posterior lateral fusiform (LPF)

Stimulus >>>

<table>
<thead>
<tr>
<th>Auditory</th>
<th>Tactile</th>
<th>Visual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Words</td>
<td>Words</td>
<td>Words</td>
</tr>
<tr>
<td></td>
<td>Objects</td>
<td>Colours</td>
</tr>
</tbody>
</table>

Task >>>

Stimulus-response computations that activate left LPF

One process or multiple processes?

What do brain areas do?
We may need to change our cognitive theory before the mapping can be done – a theory of cognition shaped by ‘the way the brain does things’

Price & Friston (2005)
Conventional ontology

Price & Friston (2005)
Conventional ontology

Integrated ontology (anatomically informed)

Functional labels constrained by anatomical response – only one function per cortical region

Price & Friston (2005)
Integrating levels

Dialogue

Neuroscience

Psychology

Computer models

Education
Integrating levels

Brain data    Genetic data

What does it mean?

How does it work?

Behavioural data    Classroom data
Computers

- Computational methods in educational neuroscience:
  - Cognitive modelling
  - Intelligent tutoring systems
  - Adaptive microworlds

- Methods share a requirement to understand learner and way experience and feedback can advance knowledge

- Types of model
  - Artificial neural networks
  - Symbolic models (ACT-R)
Artificial neural networks

Hebbian learning: “neurons that fire together wire together”
How it works is important
Broad themes

- **Neuroconstructivism** – a theoretical perspective that argues that the way a cognitive system (the ‘mind’) is implemented in the brain makes certain ways of thinking and learning easier and others harder.

- Cognitive theory is constrained by brain function.

- The mind is not an *ipad*, and this has implications.
• Knowledge is hard to move around the system because it is built into the structure.
• This is an implementation constraint – *knowledge and process are combined*
OLD

Lots of Hz

CPU Working memory Long-term memory

Movement of information Movement of information

RAM Hard disk

NEW

• “Given my current goal, which bits of the computer should be working right now?”

Modulatory system

Episodic memory

Content-addressable, active processing system (combines CPU + WM + hard disk)

(to move info from Episodic to Long-term, have to shut the system down overnight...)
Broad themes

• Lessons of neuroconstructivism for education
  – Brain is not an automatic abstractor, likes to retain sensorimotor codes where possible
  – Brain activates partial representations of knowledge relevant to task context – multiple contexts are required to learn abstract concepts (i.e., all contexts)
  – Brain systems are specialised – no jack-of-all-trades (including working memory!)
  – Brain structures become functionally more tuned through practice – educational abilities require sculpting of new systems from raw material provided by evolution (evolution may resist!)
  – Emotions / rewards modulate plasticity
Broad themes

• Lessons of neuroconstructivism for education
  – Training of the modulatory system is important
  – Timing is important – plasticity changes with age
  – Details of the consolidation process are important: i.e., how knowledge enters structure
  – Delivery of energy to the brain is important
Examples of models

- Sensitive periods in development
  - Thomas & Johnson (2006)

- Development (and intervention) in autism
  - Thomas, Knowland & Karmiloff-Smith (2011)

- Variation in cognitive abilities across populations
  - Thomas, Ronald & Forrester (submitted), Thomas & Knowland (submitted)
Sensitive periods

• Mechanisms that reduce functional plasticity
  – Loss of computational resources (e.g., connectivity)
  – Perceptual assimilation
  – Competition for resources between different skills
  – Entrenchment
  – Change in local excitatory/inhibitory balance

• Ways to release plasticity
  – More practice / accept lower ultimate proficiency
  – Change task to rely on computationally efficient strategies (explicit rules)
  – Exaggerate key perceptual dimensions
  – Cease competing skills
  – Pharmacologically alter excitation/inhibition balance (risky!)
Development in autism

• Proposals of low-level neurocomputational causes of autism
  – Atypical category formation, atypical neural codes, or connectivity disruptions

• Over-aggressive synaptic pruning (Thomas, Knowland & Karmiloff-Smith, 2011)
  – Explains onset of symptoms in second year
  – Demonstrates more systematic domains are more readily acquired given over-pruned system
  – Demonstrates deficits are relatively insensitive to environment (unless extremely deprived)
  – Indicates likelihood of protective and risk factors acting at synapse
  – Predicts interventions will not normalise the system
Terry Jernigan’s challenge

• ‘Integrative models must somehow reconcile apparently disparate research trends’
  – High heritability of cognitive phenotypes
  – High heritability of neural architecture
  – Modest associations between neural architecture and cognitive differences
  – Dynamic neuroplastic responses to training
  – Strong dependency of level of expertise on practice
  – (Environment has differential effects across cognitive domains, e.g., as measured by socioeconomic status)

• How can this possibly all fit together? How do genes and environment fit together? *How does it work?*
Population-level modelling
Simulate 1000 individual trajectories of development (example domain from language)

- Output units
- Internal units
- Input units

Variability in genome

Variability in environmental input

Create MZ and DZ twin pairs to measure heritability…

Developmental process
Cognitive models are fairly rudimentary in terms of neural realism but can still offer interesting ideas on the relation of brain to behaviour.

Prune unused connections

Gives us an idea what computational properties grey matter and white matter volumes correspond to.
Population development
Heritability

Behaviour is highly heritable (genetic)

But note: development is entirely dependent on experience (practice)
Correlations

<table>
<thead>
<tr>
<th></th>
<th>“Grey matter”</th>
<th>“White matter”</th>
<th>Behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Grey matter”</td>
<td>1</td>
<td>.61</td>
<td>.11</td>
</tr>
<tr>
<td>“White matter”</td>
<td></td>
<td>1</td>
<td>.02</td>
</tr>
<tr>
<td>Behaviour</td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Modest associations between network structure and behavioural differences

e.g., Posthuma et al. (2003)
Simulated association analyses

More systematic domain >>> (Regular verbs)

Associations alter across development and across behavioural measure

More idiosyncratic domain >>> (Irregular verbs)
Simulating SES effects on language development

- The target domain of the model was the acquisition of inflectional morphology, part of grammar.
- SES effects are uneven across language – more for phonology and vocabulary (~30%), less for grammar (~5%).
Simulating SES effects on language development

• Model findings:
  – empirical data for grammar best captured by
    • relatively wider variation in learning abilities
    • relatively narrow variation in (and good quality of) environmental information
  – more systematic domains (i.e., with rules) are less vulnerable to inconsistent environment than idiosyncratic domains
  – good environment predicts success but bad environment does not predict failure
    • confirmed in empirical data
  – high ability does not provide resilience to poor environment
    • gene x environment interaction
    • better environment produces divergence of ability groups / higher ability produces divergence of SES groups
Gene-environment interactions

More systematic domain >>> (Regular verbs)

More idiosyncratic domain >>> (Irregular verbs)
Tracing individual trajectories

• **Illustrative problem**
  – 40-60% of pre-schoolers identified for language delay will resolve language difficulties by school entry
  – Makes targeting early intervention difficult / inefficient

• **Why do some language delays resolve?**
  – Need to understand mechanism
Population modelling (n=1000)

- Time 1
  - Delayed
  - Normal range

- Time 2

- Time 3

- Time 4

- Time 5
Resolving language delay

- Early diagnosed delay resolves in 66% of simulated cases – why?
Inflectional morphology: Individual developmental trajectories
Mechanisms for delay

- What mechanistic differences discriminate between the groups?

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<tr>
<th></th>
<th>Computational Plasticity</th>
<th>Computational Capacity</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>Okay</td>
<td>Okay</td>
<td>Okay</td>
</tr>
<tr>
<td>Persistent deficit</td>
<td>Okay / low</td>
<td>Poor</td>
<td>Okay</td>
</tr>
<tr>
<td>Resolving low-normal</td>
<td>Low</td>
<td>Okay</td>
<td>Poor</td>
</tr>
<tr>
<td>Resolving normal</td>
<td>Low</td>
<td>Okay</td>
<td>Good</td>
</tr>
</tbody>
</table>

Challenge: to find early neural markers to differential low capacity versus low plasticity
Limitations of modelling

• The cognitive system has many interacting parts and models currently only target components

• Some phenomena are complex and not well understood (e.g., meta-cognition, teacher-child interaction) and therefore harder to model

• Education is also a classroom phenomenon – beyond the focus of the individual
What does it all mean?

• Aim to understand:
  – Mechanistic principles of how the brain acquires, consolidates and abstracts knowledge
    • To optimise the timing, regimes, and contexts of learning
  – Factors that affect learning properties of brain day to day or across life span
  – Cognitive mechanisms in the teacher
    • Representation of learner’s current state, use of feedback to progress knowledge
  – Source of individual differences in all these aspects
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