Neural Computation

Models of prefrontal cortex function

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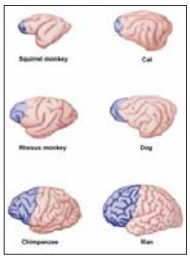
Overview of Lecture

- Prefrontal cortex (PFC)
  - what does it do?
  - what happens when it is damaged?
- Models of PFC function
  - how can they simulate the effects of PFC damage?
  - what can we learn from these simulations?

Prefrontal cortex



- Cortical region of the frontal lobe anterior to the primary and association motor cortices

Prefrontal cortex

- Thought to be involved in higher-level cognitive functions, e.g.
  - "working memory"
    - maintenance and manipulation of information over a brief interval of time, e.g. remembering a phone number
  - "executive functions"

Executive Functions

- Umbrella term for processes that control behaviour.
- Allow us to co-ordinate psychological processes (attention, memory, perception etc.) in order to achieve goals

e.g. BLUE

Executive functions

- Executive Functions include:
  - Inhibition
  - Flexibility
  - Planning
  - Multitasking
  - Judgement / synthesis

Executive functions

- Executive Functions include:
  - Inhibition

Stroop Task

Stroop task

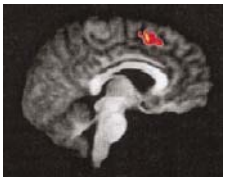
- Three types of stimuli:
  - Congruent: RED
  - Incongruent: BLUE
  - Neutral: XXXX or GREEN

Behavioural performance

Dunbar & MacLeod (1984)

Involvement of PFC

Neuroimaging (fMRI)



- Increased Stroop interference in
  - patients with PFC lesions
  - schizophrenia (thought to involve PFC dysfunction)

A model of the Stroop task

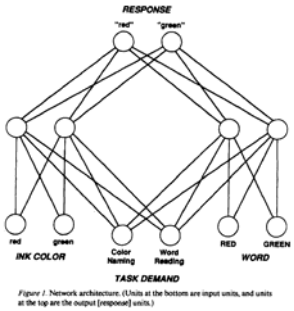
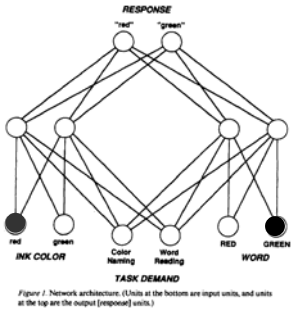


Figure 1. Network architecture. (Units at the bottom are input units, and units at the top are the output [response] units.)

A model of the Stroop task



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GREEN

A model of the Stroop task

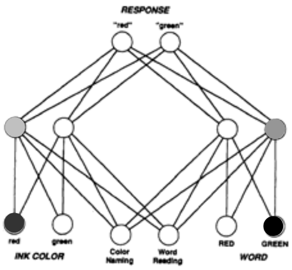
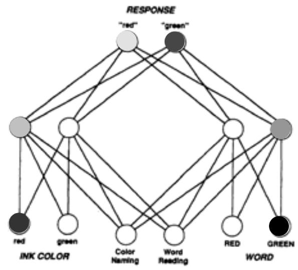


Figure 1. Network architecture. (Units at the bottom are input units, and units at the top are the output [response] units.)

GREEN

A model of the Stroop task

"Green"



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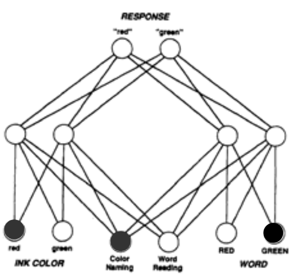
GREEN

A model of the Stroop task



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GREEN

A model of the Stroop task

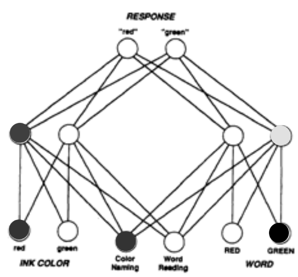


Figure 1. Network architecture. (Units at the bottom are input units, and units at the top are the output [response] units.)

GREEN

A model of the Stroop task

"Red"

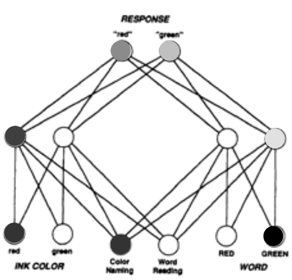


Figure 1. Network architecture. (Units at the bottom are input units, and units at the top are the output [response] units.)

GREEN

A model of the Stroop task

- Trained by backpropagation
  - more training for word-reading than colour-naming
- Processing iterated in cycles
- Trial begins with activation of input units
- Activation accrues in output units
- Trial terminated when activation level in one of the output units passes a threshold
- Number of cycles required is then recorded as "reaction time" and may be compared against human behavioural data

A model of the Stroop task

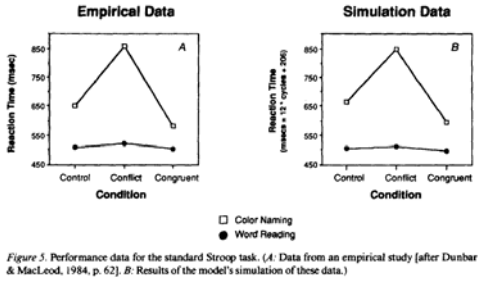
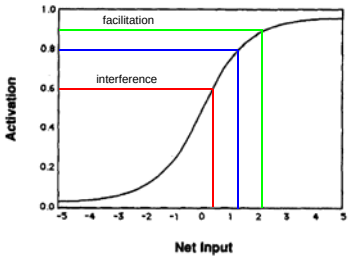


Figure 5. Performance data for the standard Stroop task. (*A*: Data from an empirical study [after Dunbar & MacLeod, 1984, p. 62]. *B*: Results of the model's simulation of these data.)

Activation function



Conclusions

- PFC plays a role in biasing processing along input-output pathways
- Helps to resolve competition between various response tendencies afforded by a stimulus

Conclusions

- PFC plays a role in biasing processing along input-output pathways
- Helps to resolve competition between various response tendencies afforded by a stimulus
- Is this account limited to the role of PFC in inhibition?
- Can this account predict the consequences of PFC dysfunction?

Executive functions

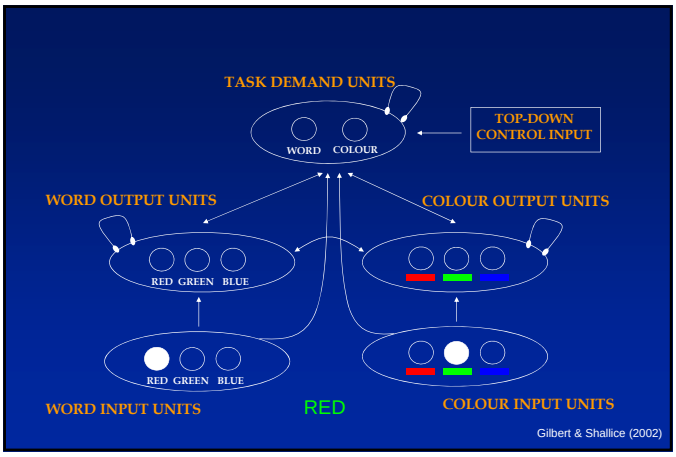
- Executive Functions include:
  - Inhibition
  - Flexibility
  - Planning
  - Multitasking
  - Judgement / synthesis

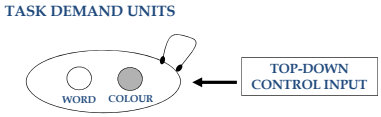
Task Switching Paradigm

- AABBAABB

Task Switching Paradigm

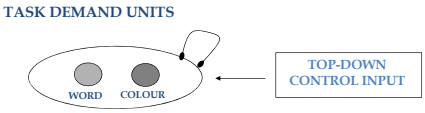
- AABBAABB
  - "Switch trial"
  - "Repeat trial"
- Switch cost = RT(switch) – RT(repeat)





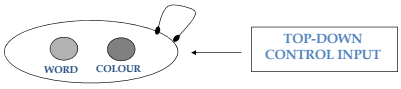
Colour naming

Gilbert & Shallice (2002)



Word reading

Gilbert & Shallice (2002)



Word reading

Weak top-down input, so competition is resolved slowly

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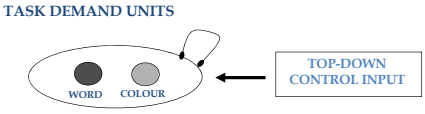
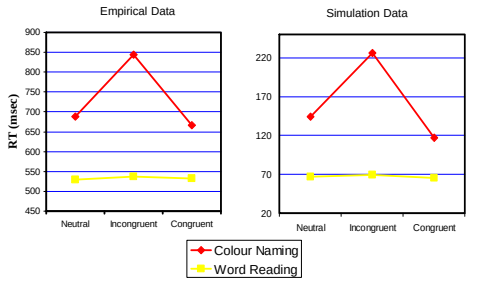


Colour naming

Strong top-down input, so competition is resolved quickly

Gilbert & Shallice (2002)



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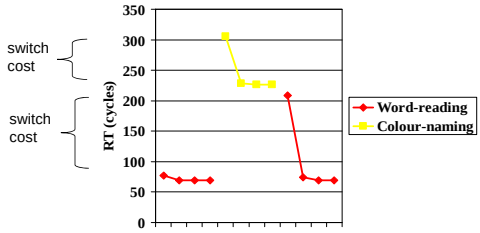

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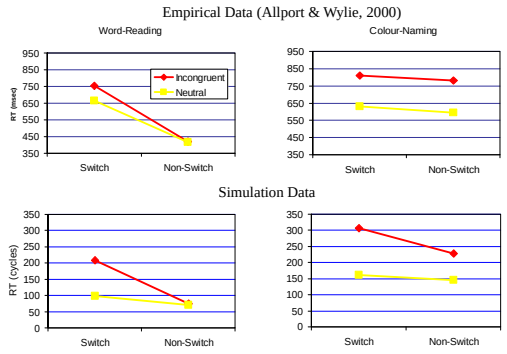


Gilbert & Shallice (2002)

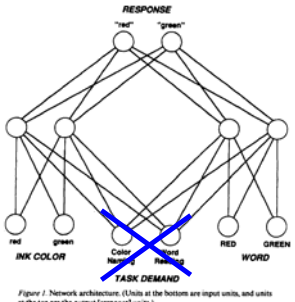
Conclusions

- Switching tasks is time consuming because of competition between previously-relevant and currently-relevant task representations
- "Inhibition" and "multitasking" may reflect similar computational mechanisms, at least in some circumstances
- NB Gilbert, Hadjipavlou & Raoelison (2013, PLoS ONE) have applied a similar model to prospective memory

Simulating the effects of PFC damage

- Can models of PFC function simulate the effects of PFC damage (e.g. schizophrenia, thought to involve PFC dysfunction)
- "Connectionist neuropsychology": lesioning connectionist networks and comparing the results to human lesion studies

Simulating the effects of PFC damage



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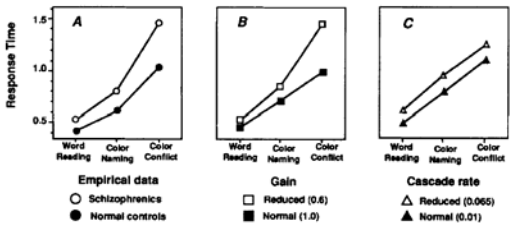
Simulating the effects of PFC damage



Cohen & Servan-Schreiber (1992)

Conclusions

- Role of PFC in many situations: represent task relevant information (e.g. behavioural goals) and bias processing pathways in posterior brain regions
- Computational models can account for a wide range of phenomena in tasks reliant on PFC function, and can account for some of the effects of PFC damage

Challenges

- How well do these models scale up (e.g. more than two tasks)?
- Where do PFC representations come from? (I.e., what is the role of learning?)
- Neuroimaging and neuropsychological studies indicate that different parts of PFC play different roles: can models incorporate these differences?
- Tasks simulated so far are generally fairly simple. What about more complex tasks?

Reading

Prefrontal cortex:

*Miller, E.K. & Cohen, J.D. (2001). An Integrative Theory of Prefrontal Cortex Function. *Annual Review of Neuroscience*, *24*, 167-202.

Gilbert, S.J. & Burgess, P.W. (2008). Executive function. *Current Biology, 18,* R110-114.

Duncan, J. (2010). The multiple-demand (MD) system of the primate brain: mental programs for intelligent behavior. *Trends in Cognitive Sciences, 14,* 172-179.

Computational models:

*Cohen, J.D., Dunbar, K. & McClelland, J.L. (1990). On the Control of Automatic Processes: A Parallel Distributed Processing Account of the Stroop Effect. *Psychological Review, 97,* 332-361

Gilbert, S.J. & Shallice, T. (2002). Task Switching: A PDP Model. *Cognitive Psychology*, *44,* 297-337.

Gilbert, S.J., Hadjipavlou, N., & Raoelison, M. (2013). Automaticity and control in prospective memory: A computational model. *PLoS ONE, 8,* e59852.

Schizophrenia:

*Cohen, J.D. & Servan-Schreiber, D. (1992). Context, Cortex, and Dopamine: A Connectionist Approach to Behavior and Biology in Schizophrenia. *Psychological Review*, *99,* 45-77

Cohen, J.D., Braver, T.S. & O'Reilly, R.C. (1996). A computational approach to prefrontal cortex, cognitive control and schizophrenia: Recent developments and current challenges. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 351(1346):*1515-27. Reprinted as chapter 14 of:

Roberts, A.C., Robbins, T.W., & Weistkrantz, L. (1998). The Prefrontal Cortex: Executive and Cognitive Functions. OUP.