


Executive Function and Intelligent Goal-directed Behavior: Perspectives from Psychology, Neurology, and Computer Science



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Pluck

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Cerone

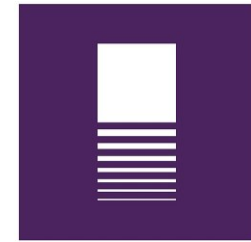
David
Villagomez-Pacheco



Chula
Chulalongkorn University



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‘Executive functions are high-level cognitive processes, often associated with the frontal lobes, that control lower-level processes in the service of goal-directed behavior’

Miyake, A., et al.: The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cogn. Psychol.* **41**, 49-100 (2000)

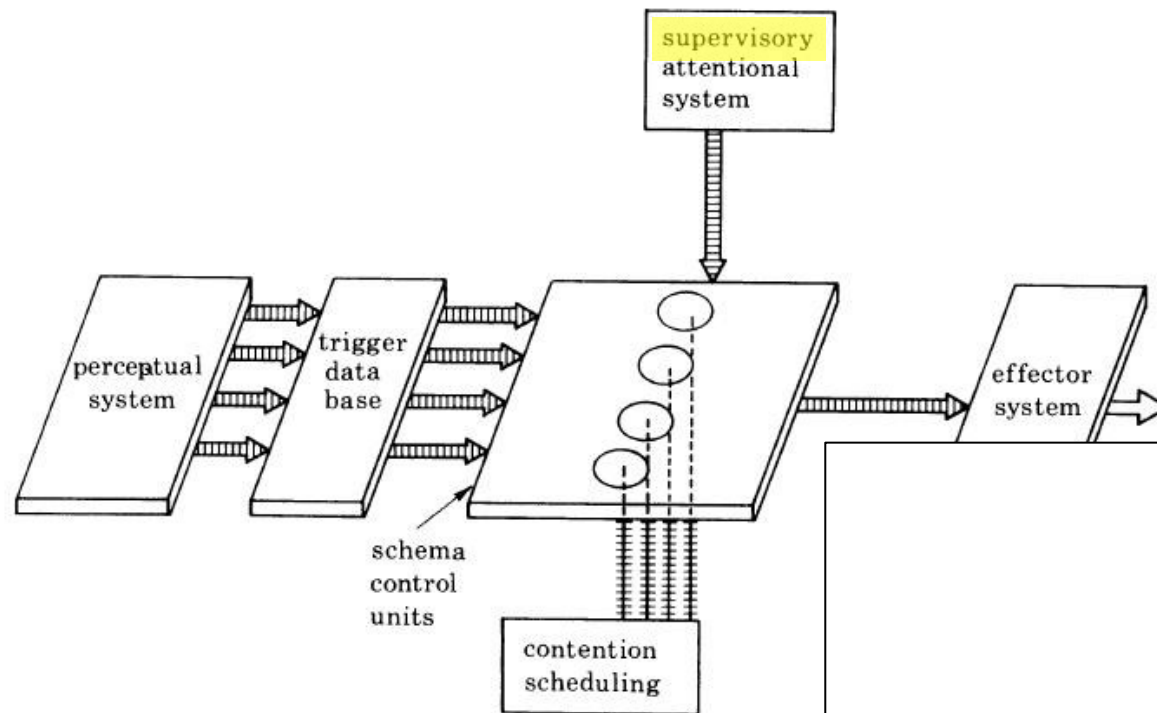
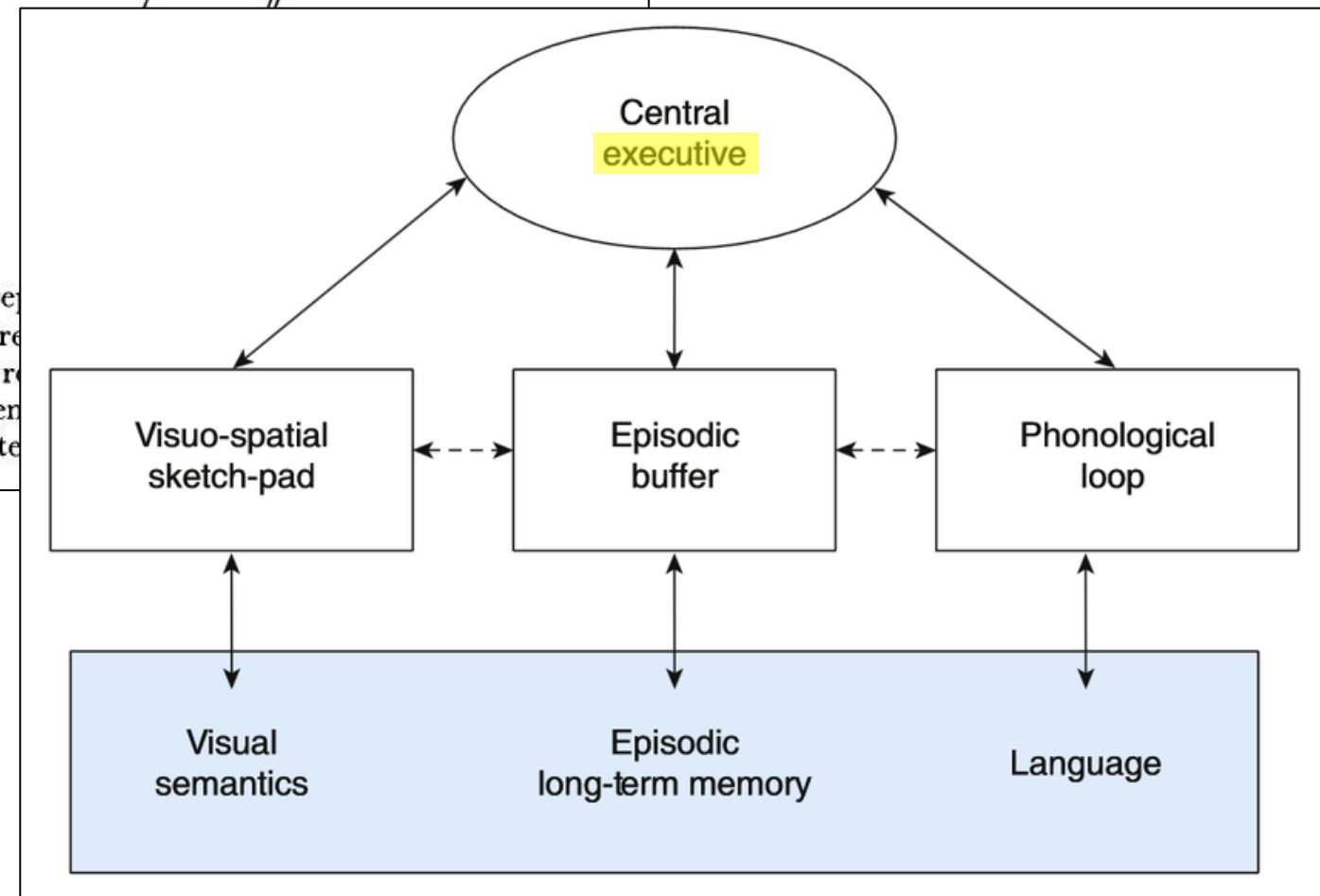


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 function of contention scheduling. The term 'effector system' re...
 involved in schema operation for both action and thought schen...
 involves placing information in short-term stores that can activate



Norman, D.A., Shallice, T.: Attention to action: willed and automatic control of behavior. Human Information Processing Technical Report no. 99 (1980).

The concept of 'executive function' originated in computer science. Programs that control other programs.

In 1956 a program called the *Automatic Supervisor* was developed for the IBM 702.

Shortly afterwards, *General Motors Executive System* was developed for the IBM 704

Moncreiff, B.: An automatic supervisor for the IBM 702. AIEE-IRE '56 Joint ACM-AIEE-IRE Western Computer Conference, pp. 21-25 (1956)



Several other top-down controllers, or operating systems were developed with similar 'executive' names.

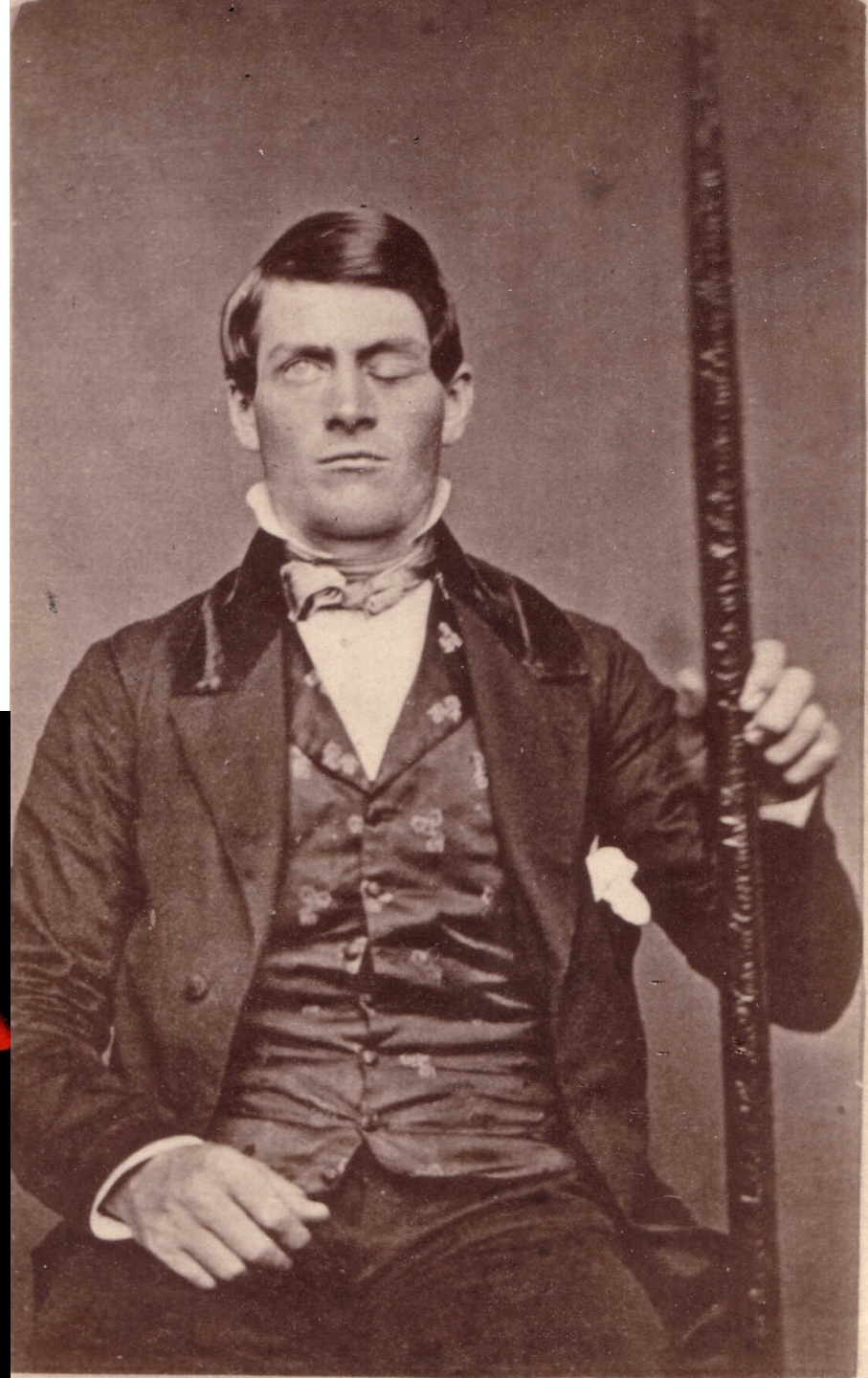
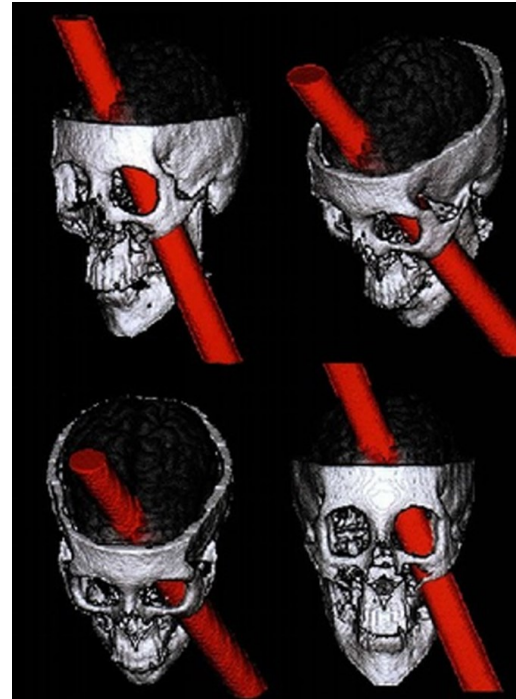
This approach in computer science coincided with the development of cognitive science, starting in 1956.

Manufacturer	Computer	Year	Operating System
Honeywell	H800	1961	Executive Monitor
Univac	Univac 1107	1962	EXEC I
Burroughs	D825	1962	AOSP
Burroughs	B5000	1962	Master Control Program
Philco	Philco-2000	1962	SYS; BKS
GE	GE-215/225/235	1962	BRIDGE
IBM	IBM 7090/7094	1962	IBSYS
Bendix	G-20	1962	EXECUTIVE
CDC	CDC 1604	1962	CO-OP monitor system
CDC	CDC 3600	1963	SCOPE monitor system
Honeywell	Honeywell 1800	1963	ADMIRAL Master Monitor
GE	GE 625-635	1964	Comprehensive Operating Supervisor
RCA	RCA 3301	1964	Realcom system
SDS	SDS 9000	1964	MONARCH
DEC	PDP-6	1964	Supervisory Control Program

Table 1 An overview of the first operating systems offered by U.S. computer manufacturers 1960-1964

Bullynck, M.: What is an operating system? a historical investigation (1954–1964). In: De Mol, L., Primiero, G. (eds.) *Reflections on Programming Systems: Historical and Philosophical Aspects*. Springer, Cham (2018).

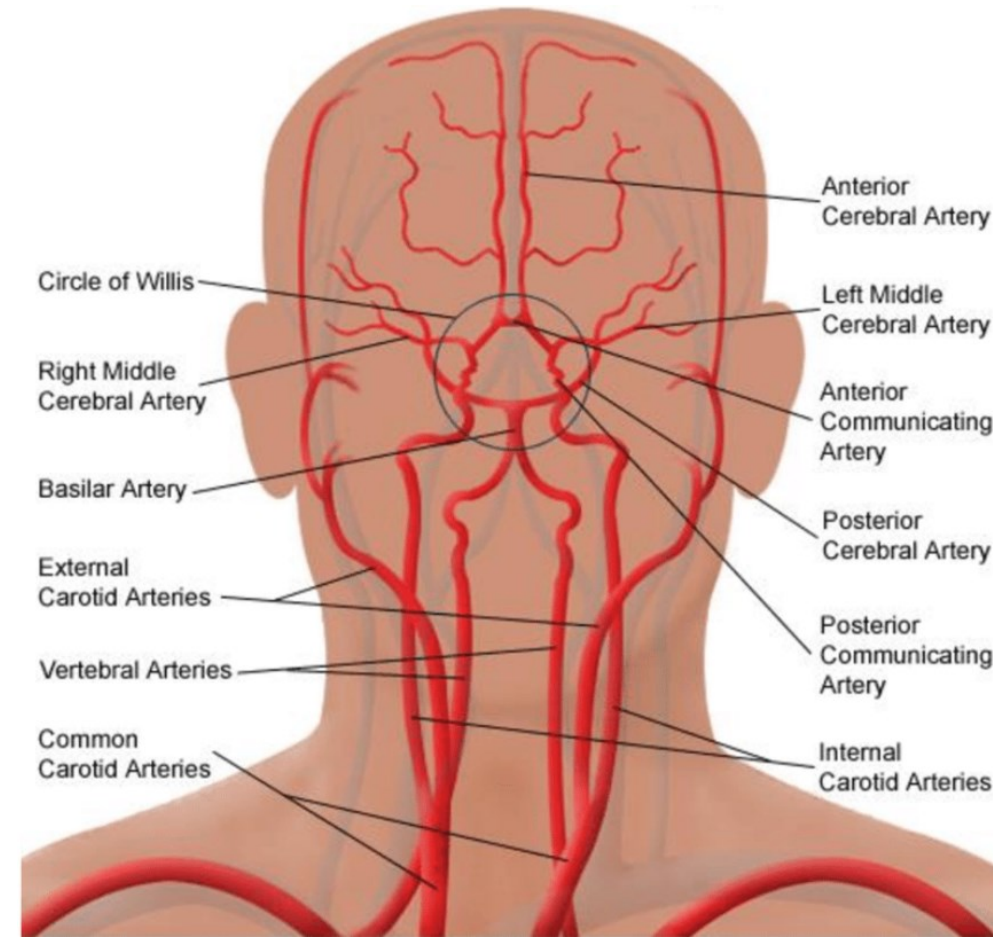
- Phineas Gage, after surviving a frontal lobe injury, became erratic, with difficulties in planning, decision making, and disinhibition.
- This pattern of symptoms is now known in neurology as the *dysexecutive syndrome*.
- Many similar cases have been reported of people with frontal lobe damage who become disorganized in the lives. Many maintain > average IQ.



Harlow, J.M.: Recovery from the passage of an iron bar through the head. *Hist. Psychiatry* 4, 274-281 (1993)

Executive control is effortful and resource demanding

- Embodied explanations argue for glucose consumption.
- Similar, neurophysiological explanations concern oxygen consumption.
- Antagonistic activity of different brain networks is a strong alternative explanation.



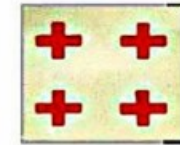
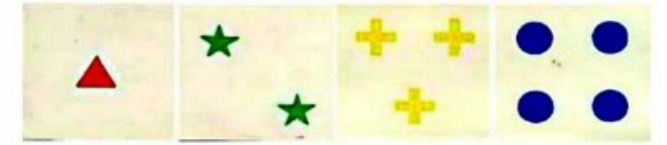
Some commonly used tests of executive function

- Saying words that begin with a letter (phonemic fluency test)
- Sorting card cards into categories and adapting when the sort rule changes (Wisconsin Card Sort Test)
- Estimating the number of camels in the Netherlands (Cognitive Estimation Test)
- Alternating between two task requirements (Trail Making Test)
- Completing sentences with a final word that makes no sense (Hayling Test)
- Repeating a string of numbers in reverse order (Digit Span test)
- Planning moves to achieve an end goal state (Towers of Hanoi)
- Naming the color of ink that color-name words are written in, e.g., **RED** (Stroop Task)



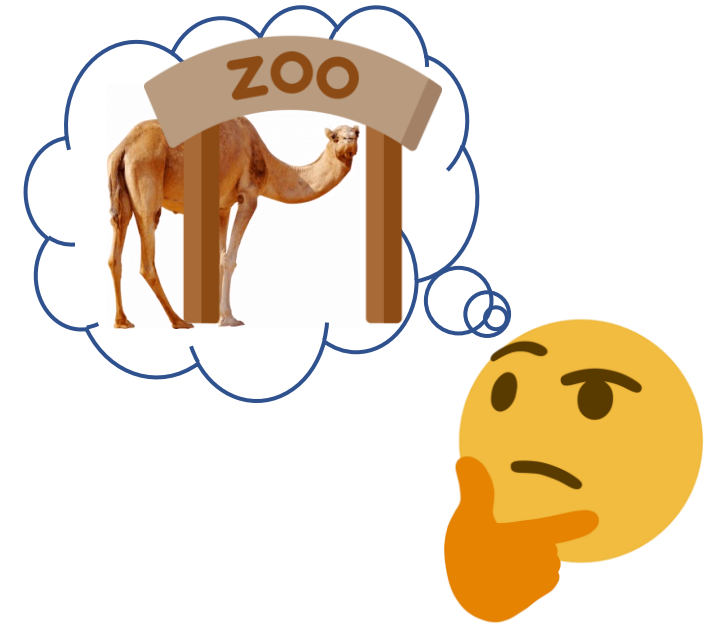
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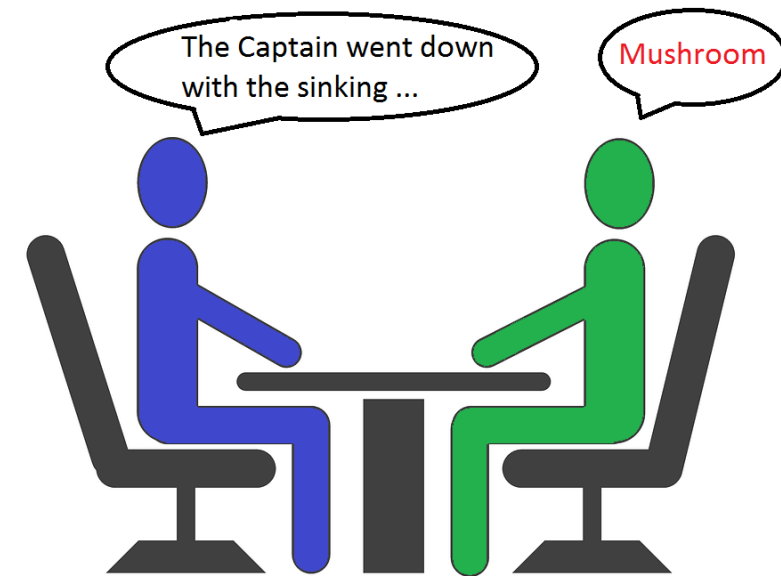
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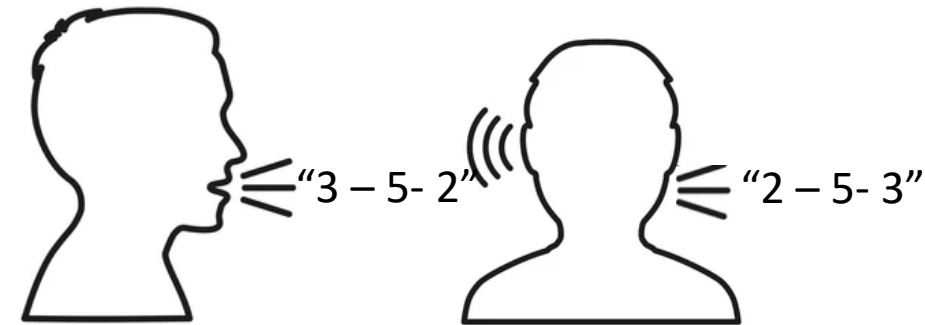
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PURPLE YELLOW RED
BLACK RED GREEN
RED YELLOW ORANGE
BLUE PURPLE BLACK
RED GREEN ORANGE

“Diversity and Unity” of Executive Functions

Response inhibition

Task switching

Updating (of working memory)

There is probably no single 'executive module'.

So, what do we actually mean by executive function?

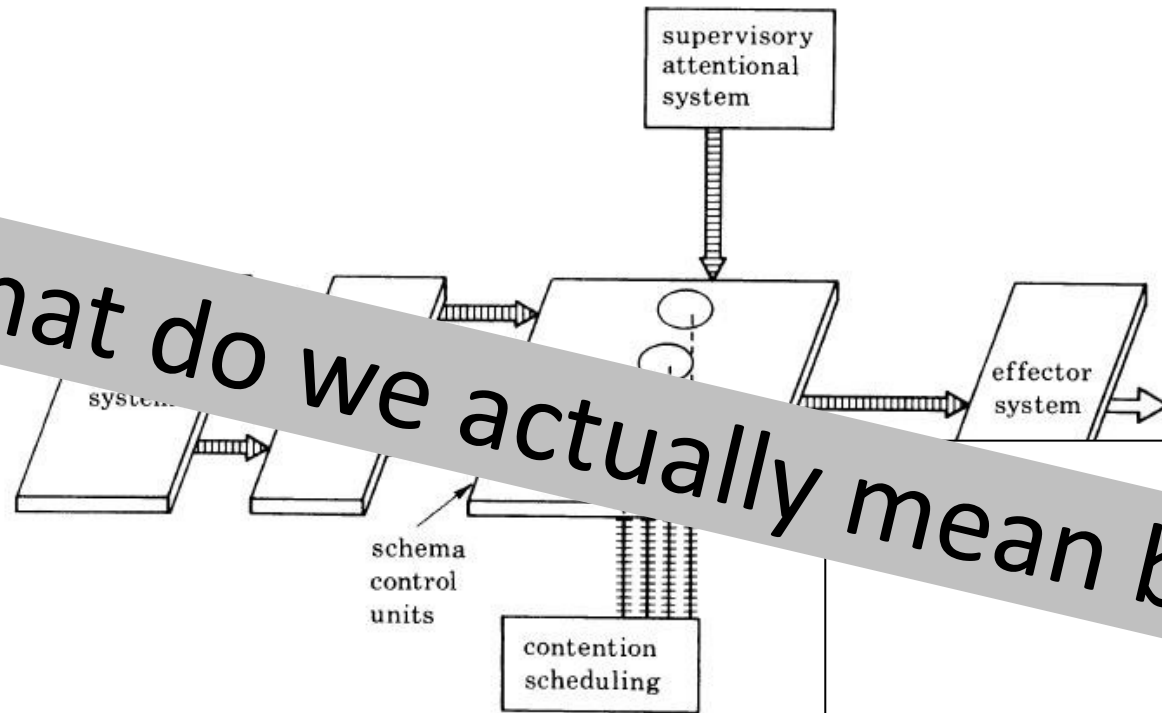
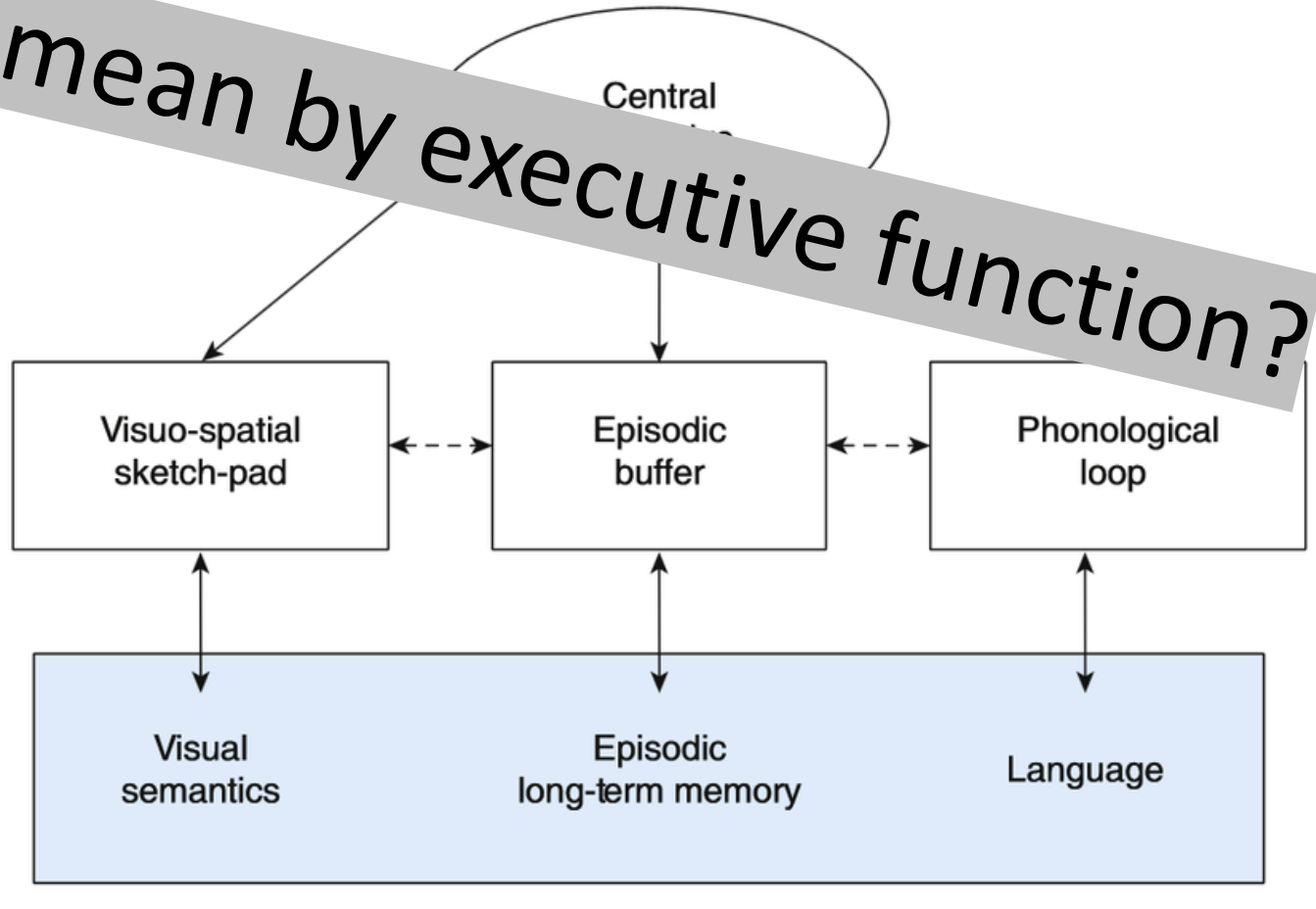
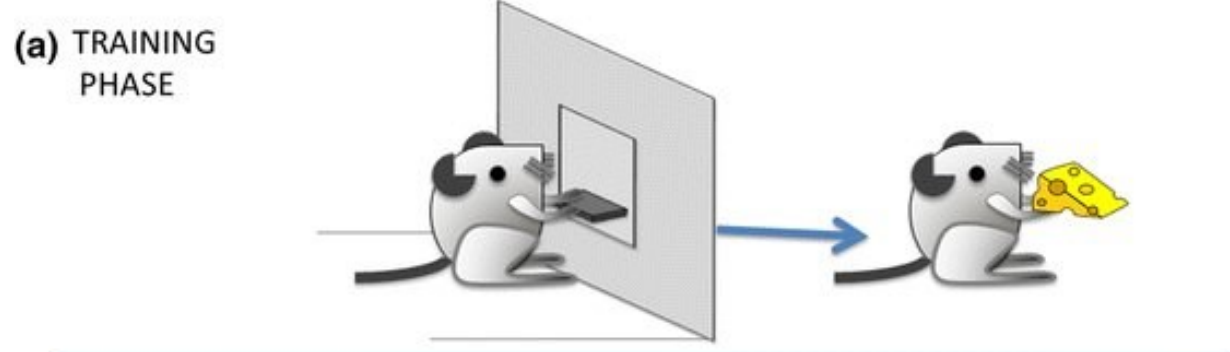


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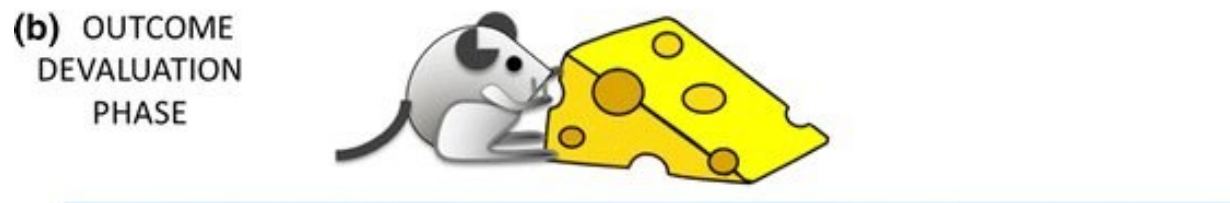


The executive component most likely fractionates into different parts.

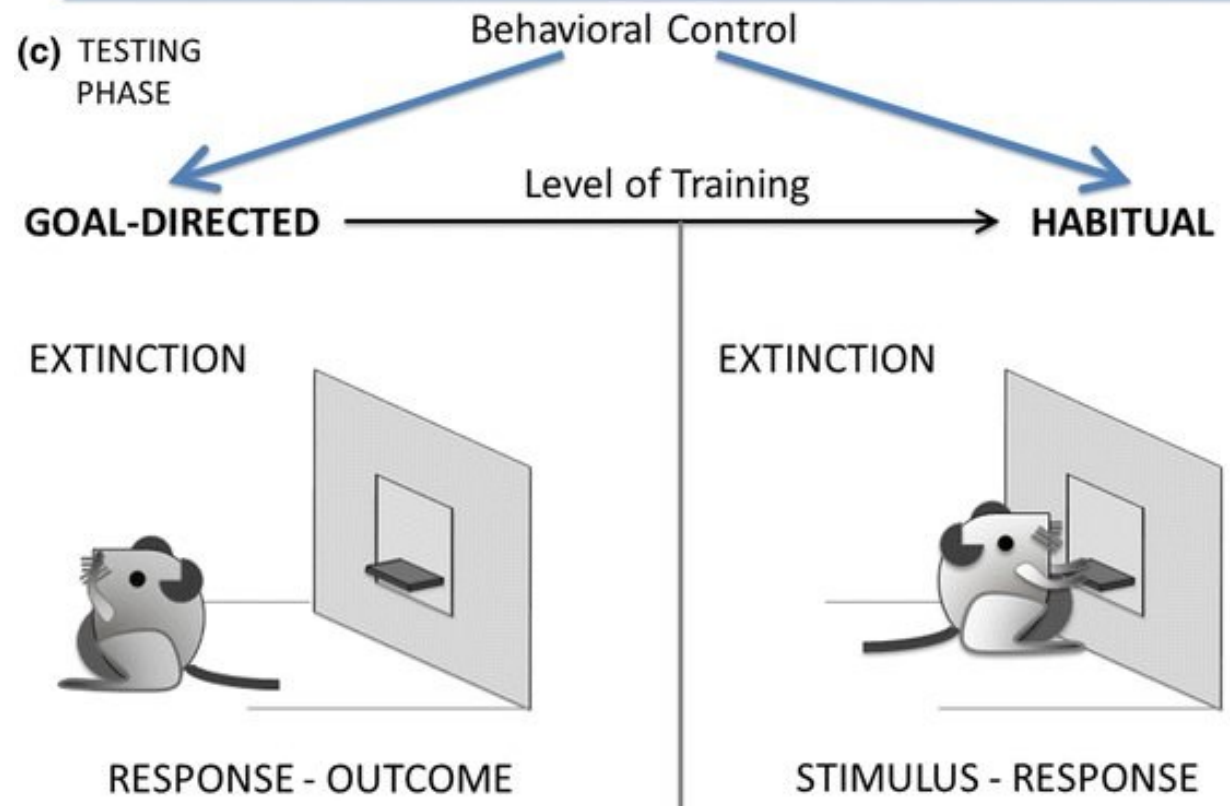
(a) A rat is trained to press a lever to obtain a reward (e.g., cheese)



(b) The cheese is devalued (e.g., by letting the rat get sated)



- (c) The rat is now tested.
- If it doesn't press the lever. Its previous lever-pressing behavior was goal-directed.
 - If it continues to press the lever, its behavior is habitual.



This distinction is equivalent to *model-based* and *model-free* in computational reinforcement learning.

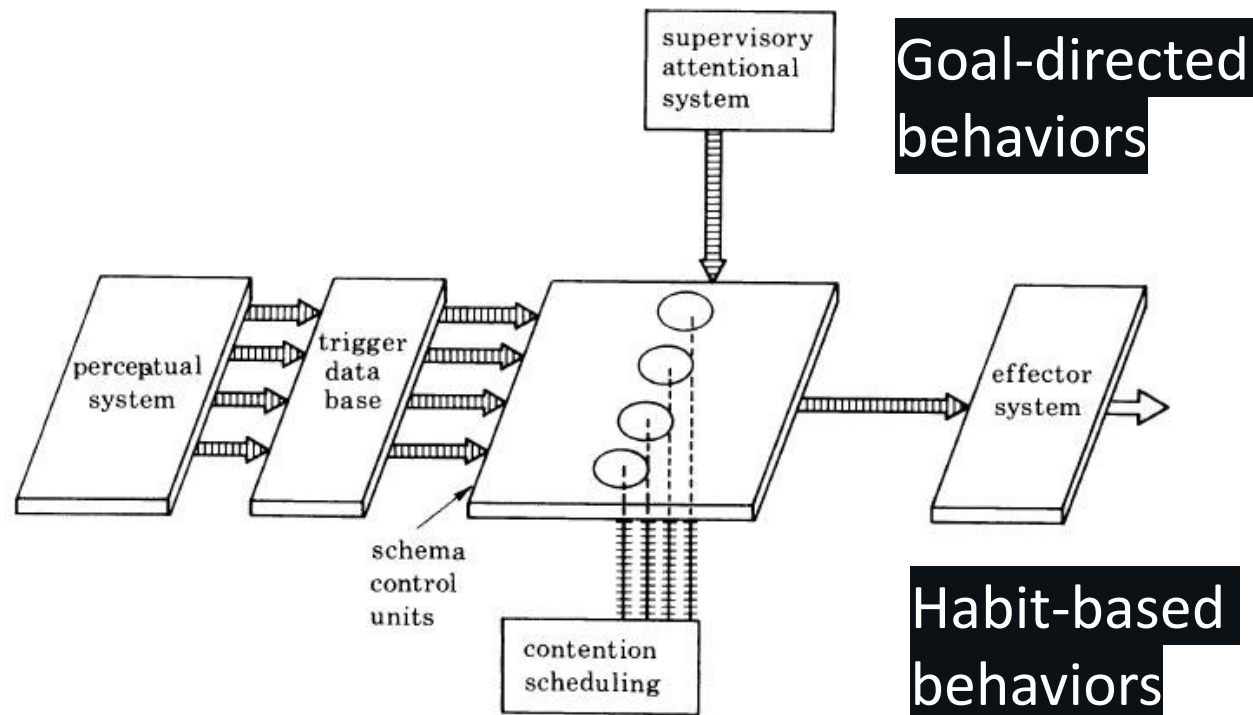


FIGURE 1. A simplified version of the Norman & Shallice (1980) model representing the flow of control information. The lines with arrows represent activating input, the crossed lines represent the primarily mutually inhibitory function of contention scheduling. The term 'effector system' refers to specific purpose-processing units involved in schema operation for both action and thought schemas. In the latter case schema operation involves placing information in short-term stores that can activate the trigger data base.

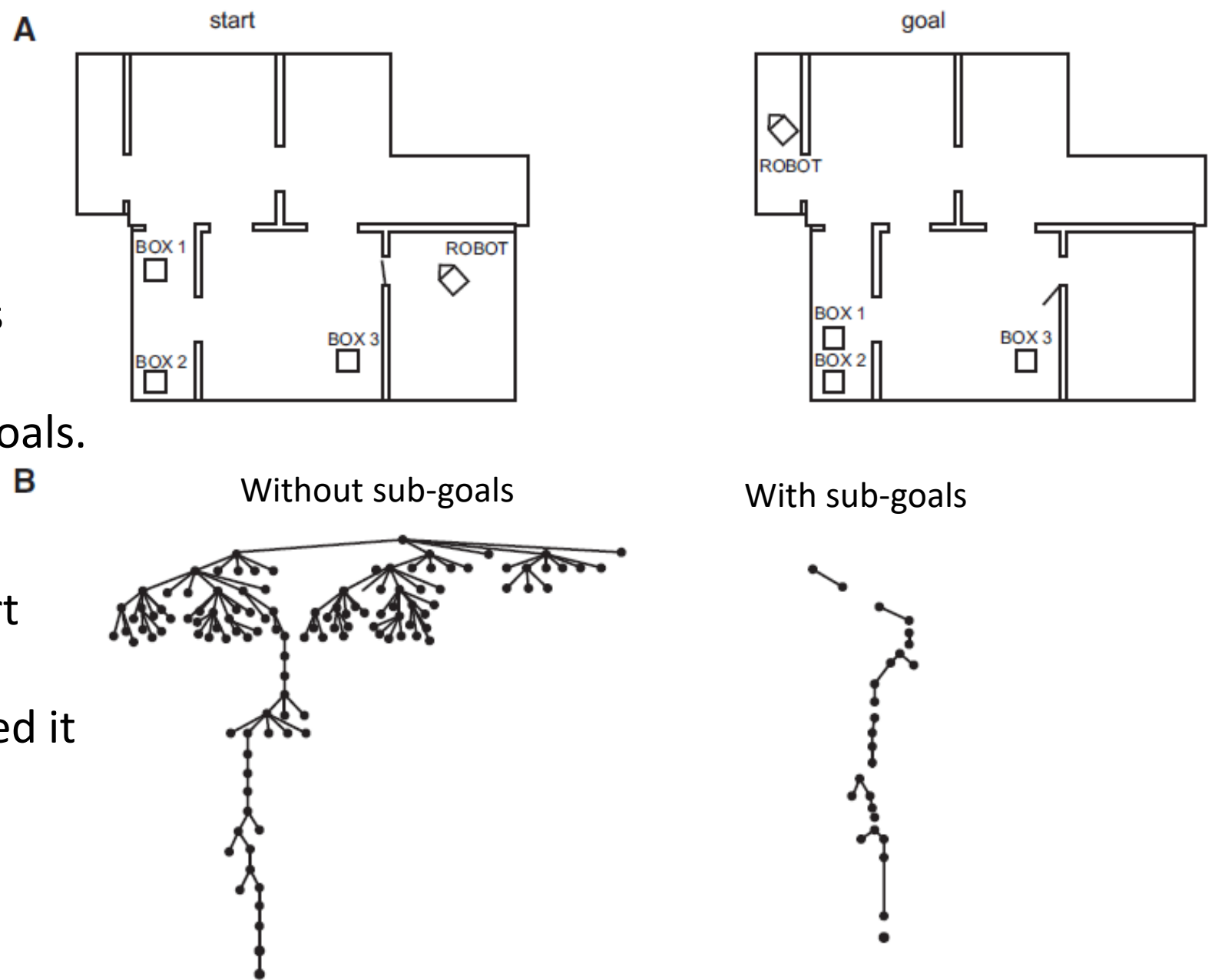
Norman, D.A., Shallice, T.: Attention to action: willed and automatic control of behavior. Human Information Processing Technical Report no. 99 (1980).

Computational-cognitive and cognitive neuroscience interpretation

Duncan has analyzed complex executive function performance as being achievable by planning and executing actions to achieve sub-goals.

In this AI example, from Sacerdoti (1974), the planned path from start state to goal state is complex and inefficient. With sub-goals identified it is efficient.

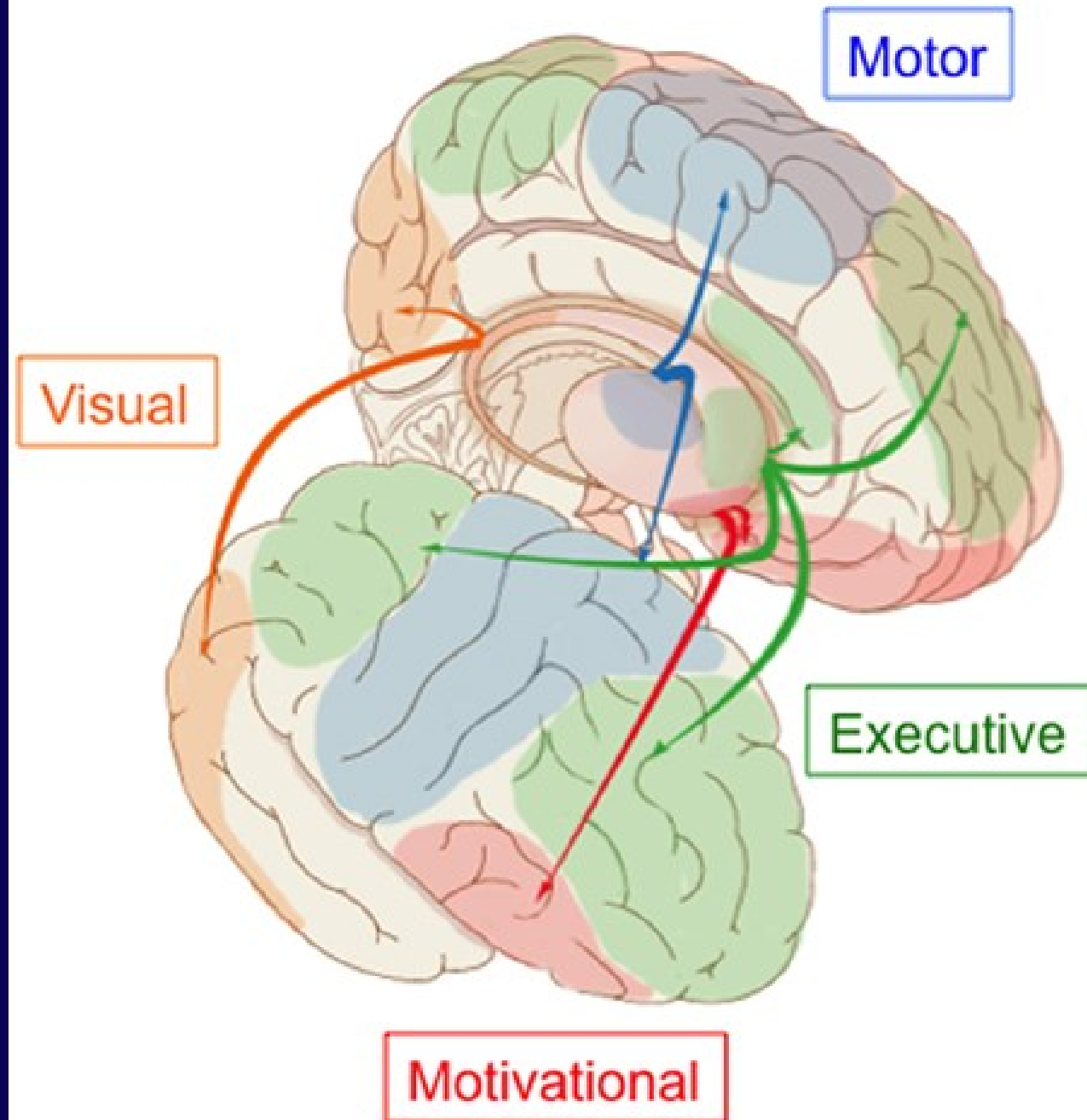
Simple goal-directed behavior can produce complex executive performance.



Sacerdoti (1974). Planning in a hierarchy of abstraction spaces. *Artif. Intell.* 5, 115–135. cited in Duncan, (2013). *The structure of cognition: attentional episodes in mind and brain.* *Neuron*, 80(1), 35-50.

- There are several cortico-subcortical loops.
- Each is based on a different area of cortex.
- Each projects to the striatum and thalamus and back to the cortex
- The loop involving dorsolateral prefrontal and posterior parietal cortices is considered the 'executive loop'.
- A simple goal-directed action is said to require >20 passes through the loop.

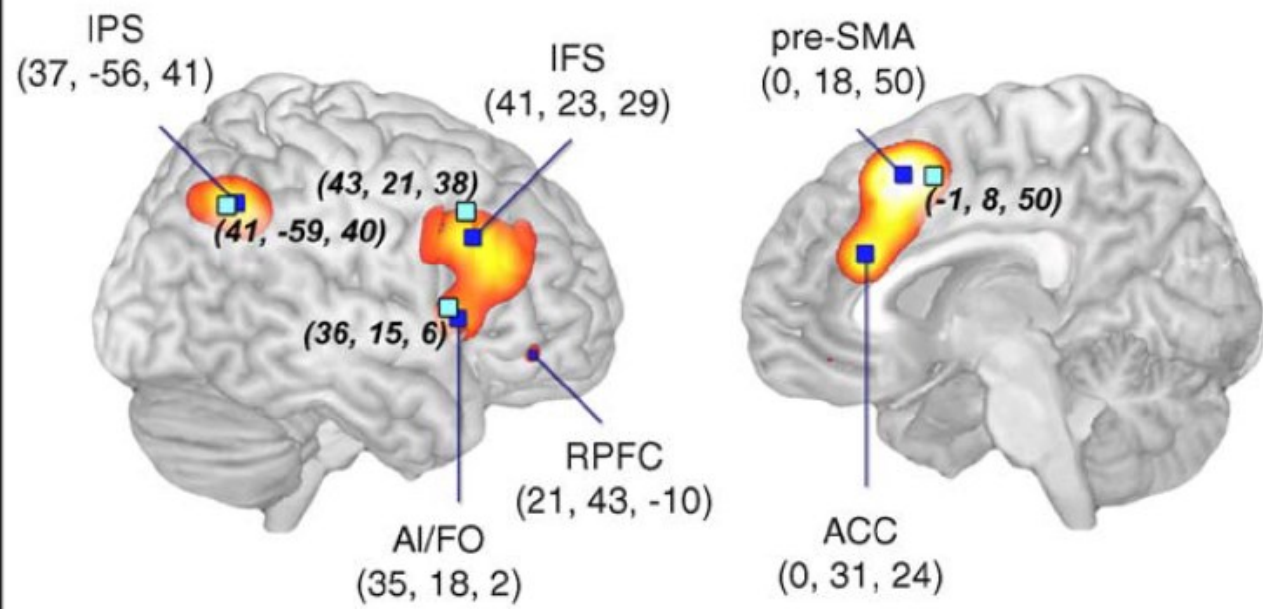
Corticostriatal Loops



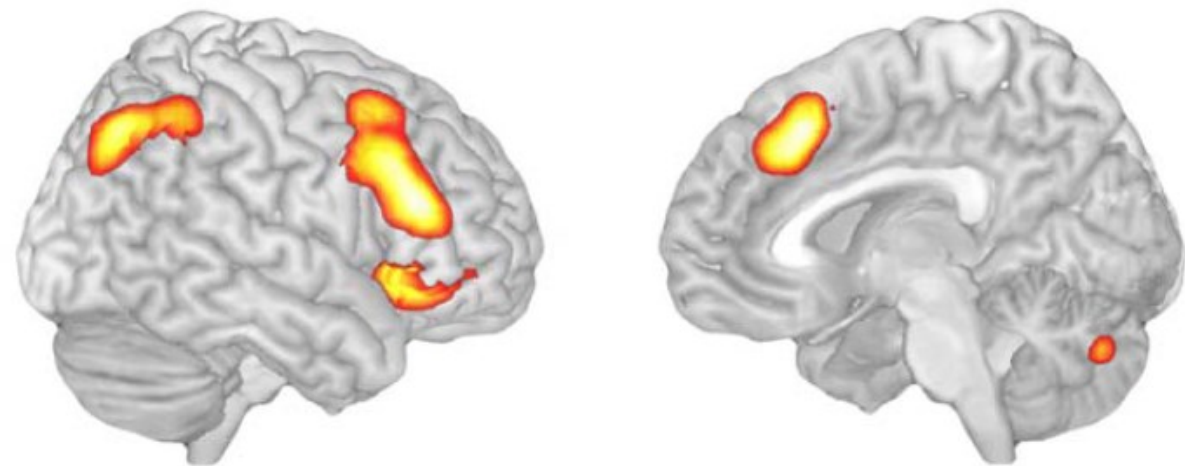
- The animal anatomy-derived executive loop fits directedly onto the 'multiple demand system' derived from functional brain imaging.
- This multiple demand system is active with any high task-load, independently of modality.
- It is also invoked by traditional fluid intelligence tests.
- This is proposed as the neurophysiological basis of both executive function and intelligence.

So, is the concept of executive function redundant?

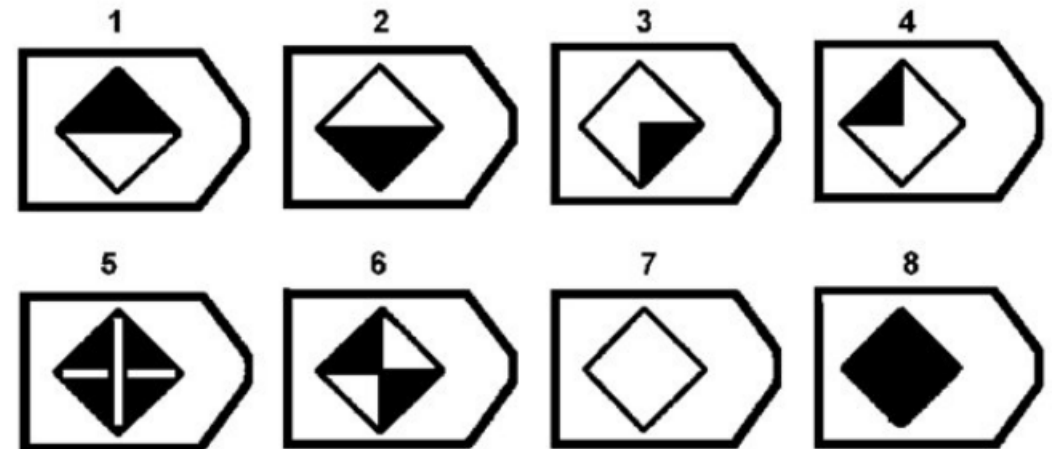
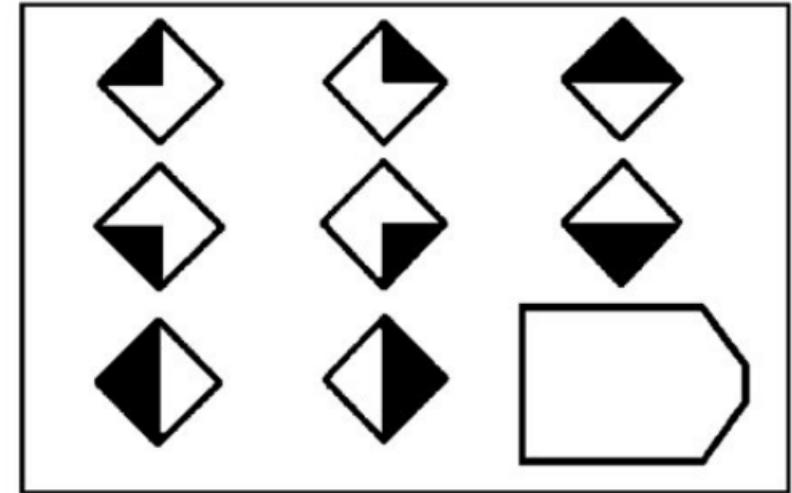
(a) Multiple Demand (MD)



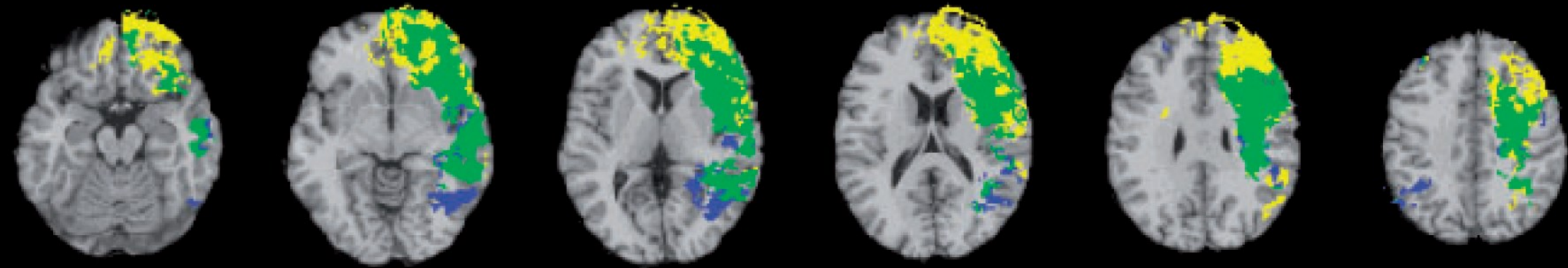
(b) Fluid Intelligence



- General intelligence (g) influences performance on all cognitive tasks.
- A typical assessment of g is this, from the Raven's Progressive Matrices.
- There is only one acceptable correct answer.
- g accounts for virtually all the variance in executive function ability.

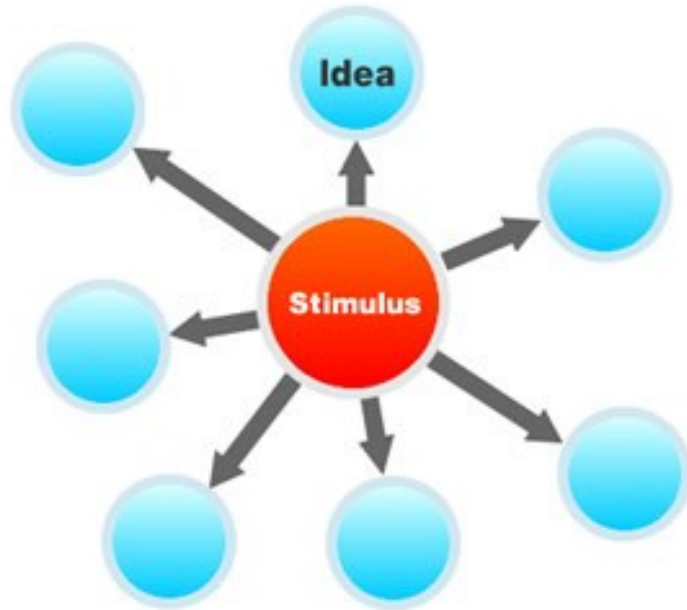


Psychometric g and executive function

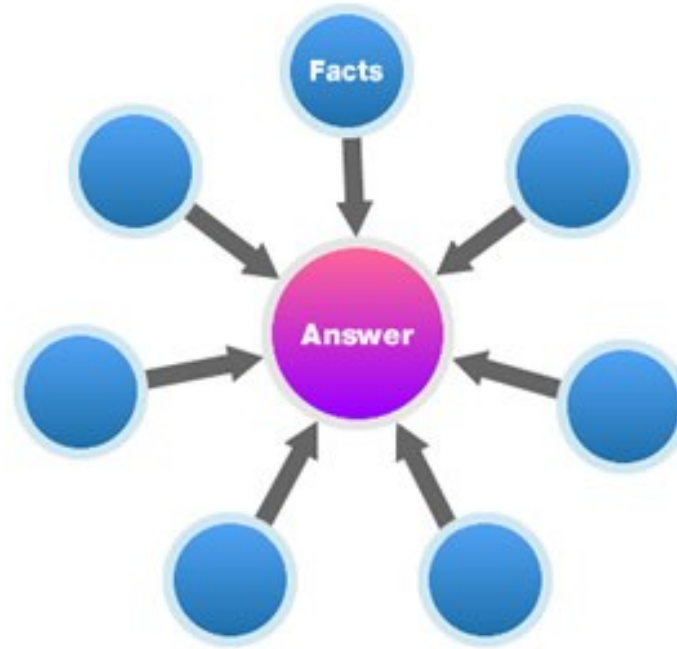


Areas of the brain, that when damaged, cause a drop in task performance. The **Green** shows overlap of areas associated with *both* drop in g and drop in executive function.

Divergent Thinking



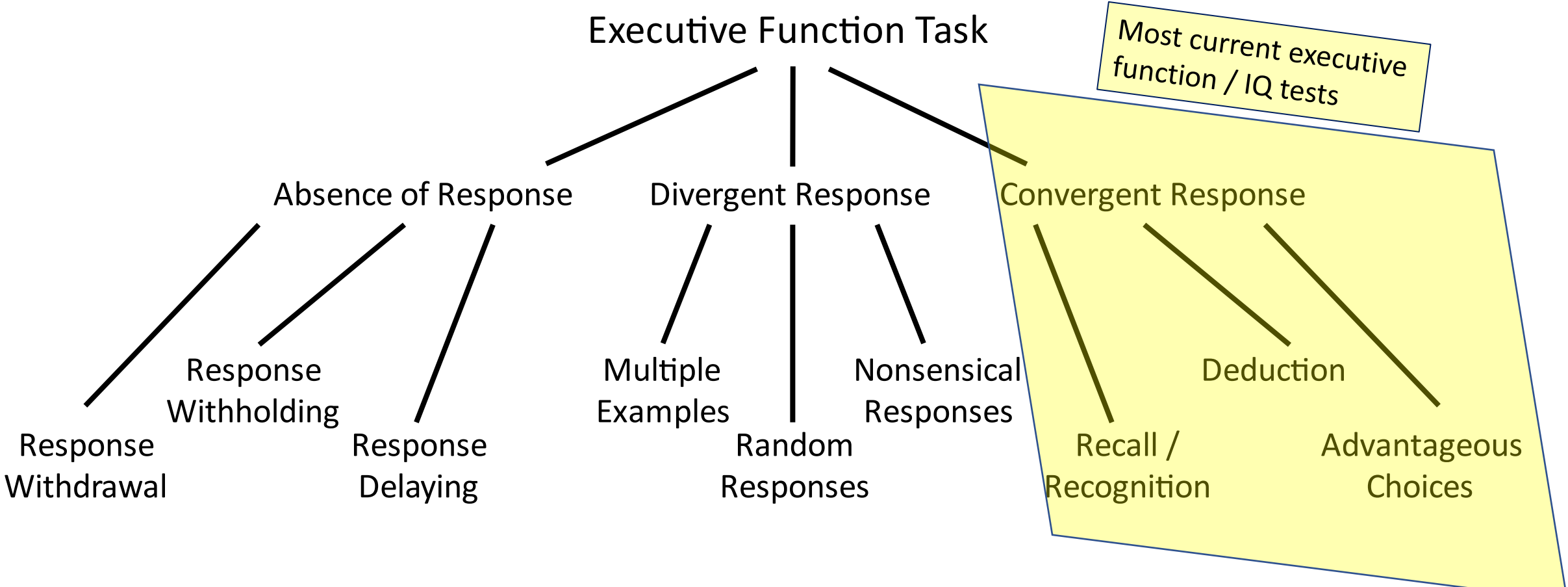
Convergent Thinking



Guilford, J.P.: The Nature of Human Intelligence. McGraw-Hill, New York (1967)

- Convergent vs divergent thinking was made popular by the psychologist J.P. Guilford.
- He was also the first psychologist to use the expression '*executive function*'.
- Divergent thinking tasks do not correlate with intelligence.
- Divergent cognitive tasks involve greater involvement of the frontal-lobes and recruit other executive-related brain networks.
- Focusing on divergent executive functions may allow the identification of executive control that involves more than fluid intelligence.

A proposed taxonomy of executive functions based on the stated goals of the task



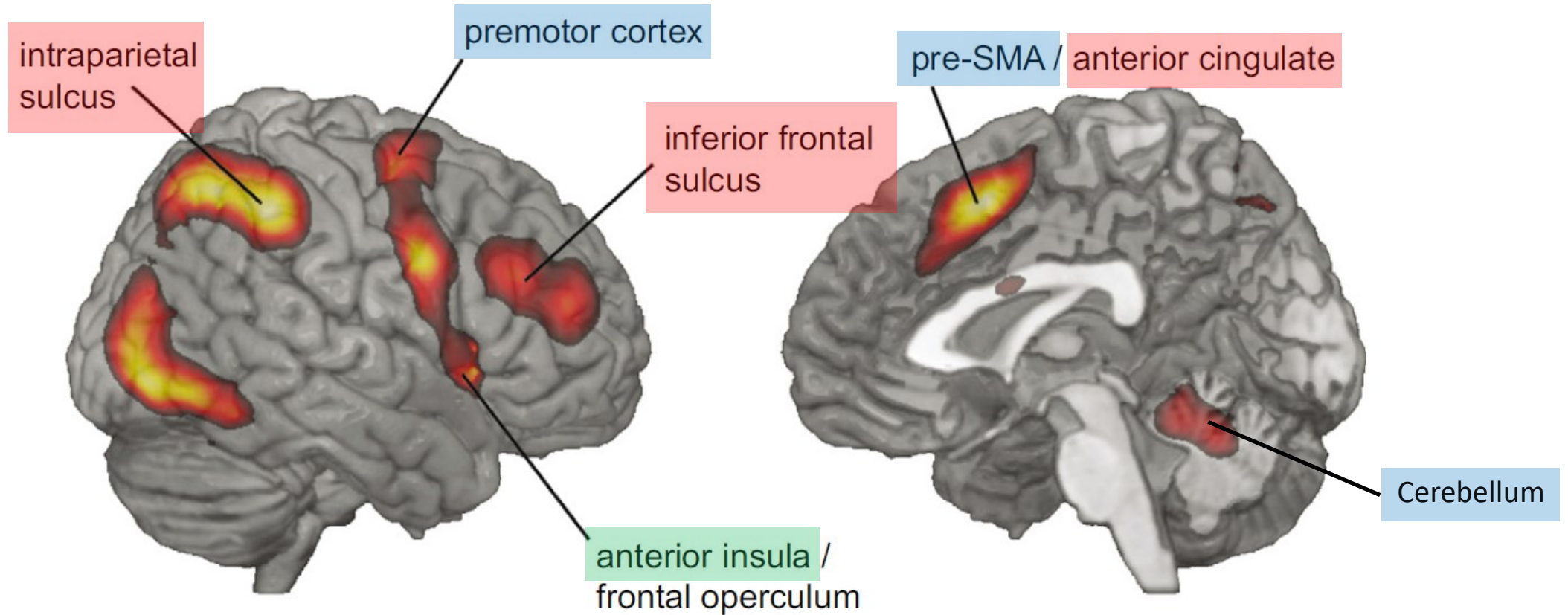
Divergent Responses / Absence Responses

- I have found that the Hayling Test (a divergent task) is a better predictor of GPA than 'intelligence' or working memory.
- It also predicts performance of car salesmen, better than 'intelligence'.
- For both GPA and sales, motor response withholding was also strong predictor of achievement.
- Perhaps, real-life intelligent goal-directed behavior is (partially) dependent on divergent cognition, and cognitive-motor integration (embodied cognition)?



- Pluck, G. et al.: Separate contributions of general intelligence and right prefrontal neurocognitive functions to academic achievement at university level. *Trends Neurosci. Educ.* 5, 178-185 (2016)
- Pluck, G. et al: Response suppression, strategy application, and working memory in the prediction of academic performance and classroom misbehavior: A neuropsychological approach. *Trends Neurosci. Educ.* 17, 100121 (2019)
- Pluck, G., et al.: Executive functions and intelligent goal-directed behavior: A neuropsychological approach to understanding success using professional sales as a real-life measure. *Psychol. Neurosci.* (2020)

fMRI data showing the cortical areas that show increased activity with cognitive load: the 'multiple demand system'



Areas very frequently associated with cognitive processing

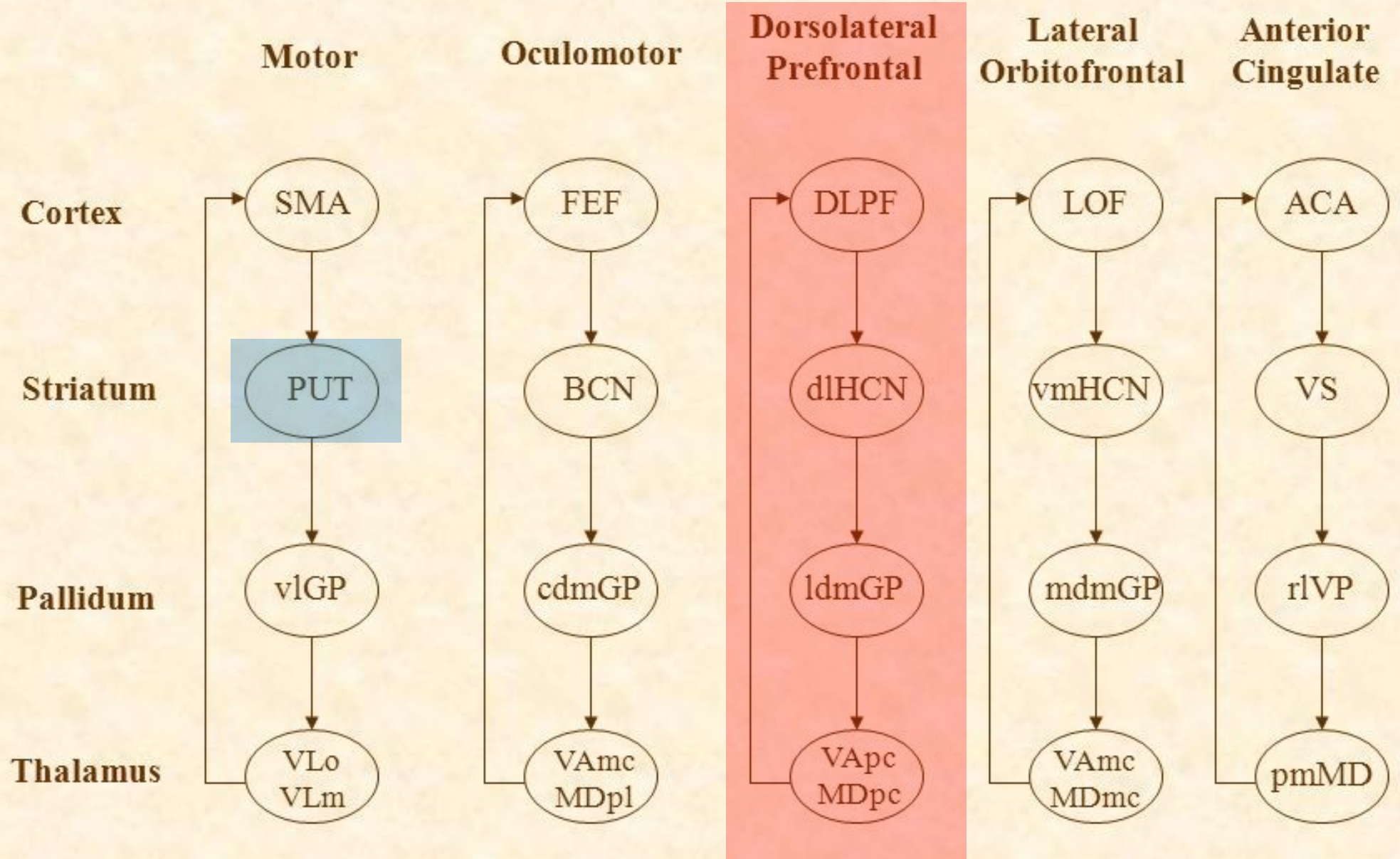
Areas very frequently associated motor control

Area associated with Interoception / homeostasis

The 'executive circuit'

Additional subcortical aspect of the multiple demand system

This probably occurs because goal-directed action, when repeated, will become habit, aka procedural memory. It thus has to involve the motor circuit.



Alexander, DeLong, & Strick, 1986

Executive function, as a cognitive skill, drives intelligent goal-directed behavior.

But it is conceptually confused with intelligence (a psychometric construct).

The analysis of motor response **withholding/withdrawing/slowing** and with **divergent** executive task performance may allow the disambiguation of intelligence from executive function.



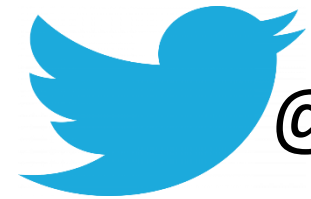
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