Trends in
Cognitive Sciences

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Feature Review

Rationalizing constraints on the capacity for cognitive control

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Why are some of us more distracted than others?

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(1) Be more flexible with switching tasks

Why are some of us more distracted than others?

(1) Be more flexible with switching tasks

(2) We have limited mental resources and being focus = paying some opportunity cost

Two Remarkable Human Cognitive Constraints

Humans are remarkably limited in

(1) **Multitasking:** How many tasks they can execute simultaneously;
(2) **Control Intensity:** How intensely they can focus on a single task.

WHY?

Two Remarkable Human Cognitive Constraints

Humans are remarkably limited in

(1) **Multitasking:** How many tasks they can execute simultaneously;
(2) **Control Intensity:** How intensely they can focus on a single task.

…There is a **tradeoff between stability and flexibility**, e.g., the more control we allocate to a task, the harder to switch, vice versa

The Stability-Flexibility Tradeoff

- **Cognitive Stability: maintain & protect task goals in the face of distraction.**
  - e.g., say “red” when seeing the word “Green” colored in red in the Stroop task.
- **Cognitive Flexibility: reconfigure quickly to switch to a different task.**
  - e.g., switch from name the color to reading the word in Stroop task.

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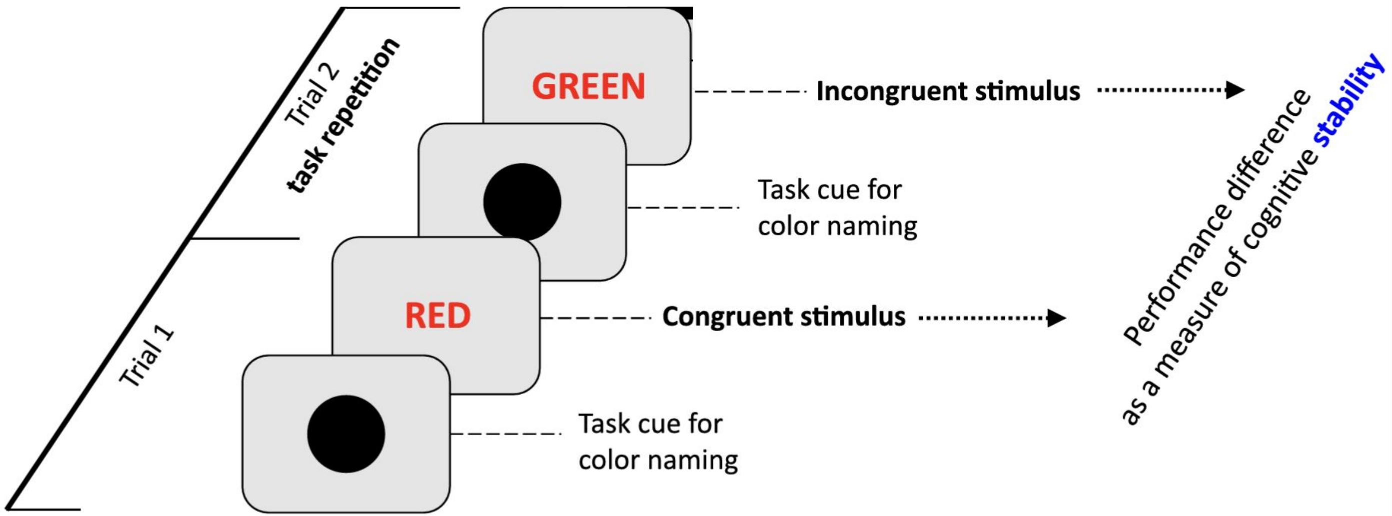
  - e.g., switch from name the color to reading the word in Stroop task.

This tradeoff is supported empirically!

Empirical Measurement of Individual **Stability** & Flexibility



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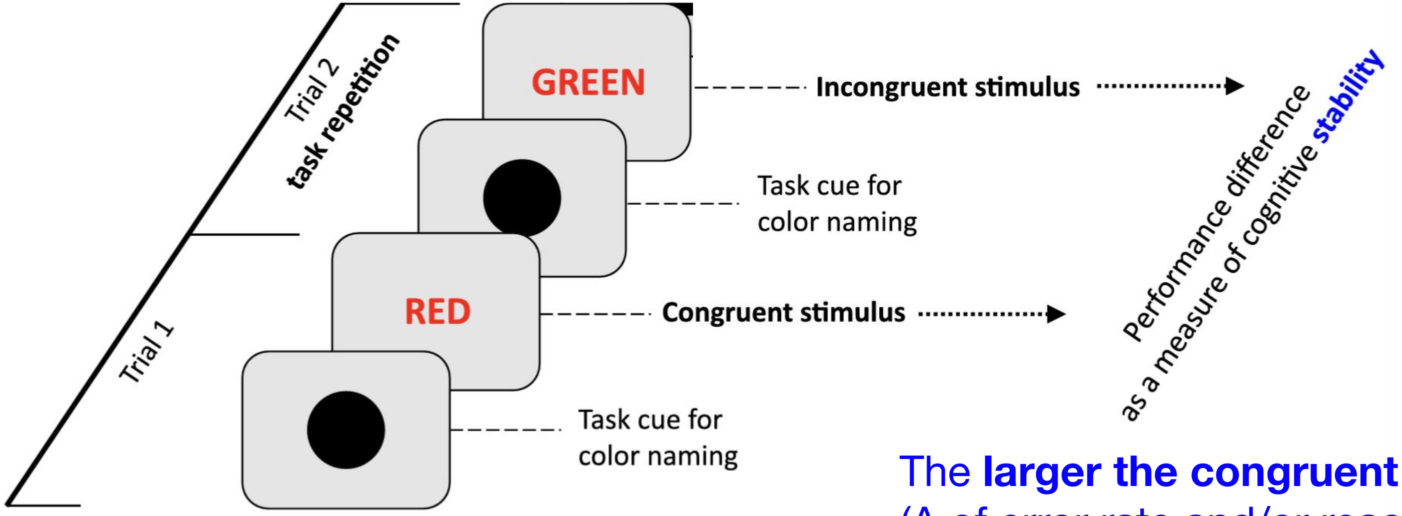
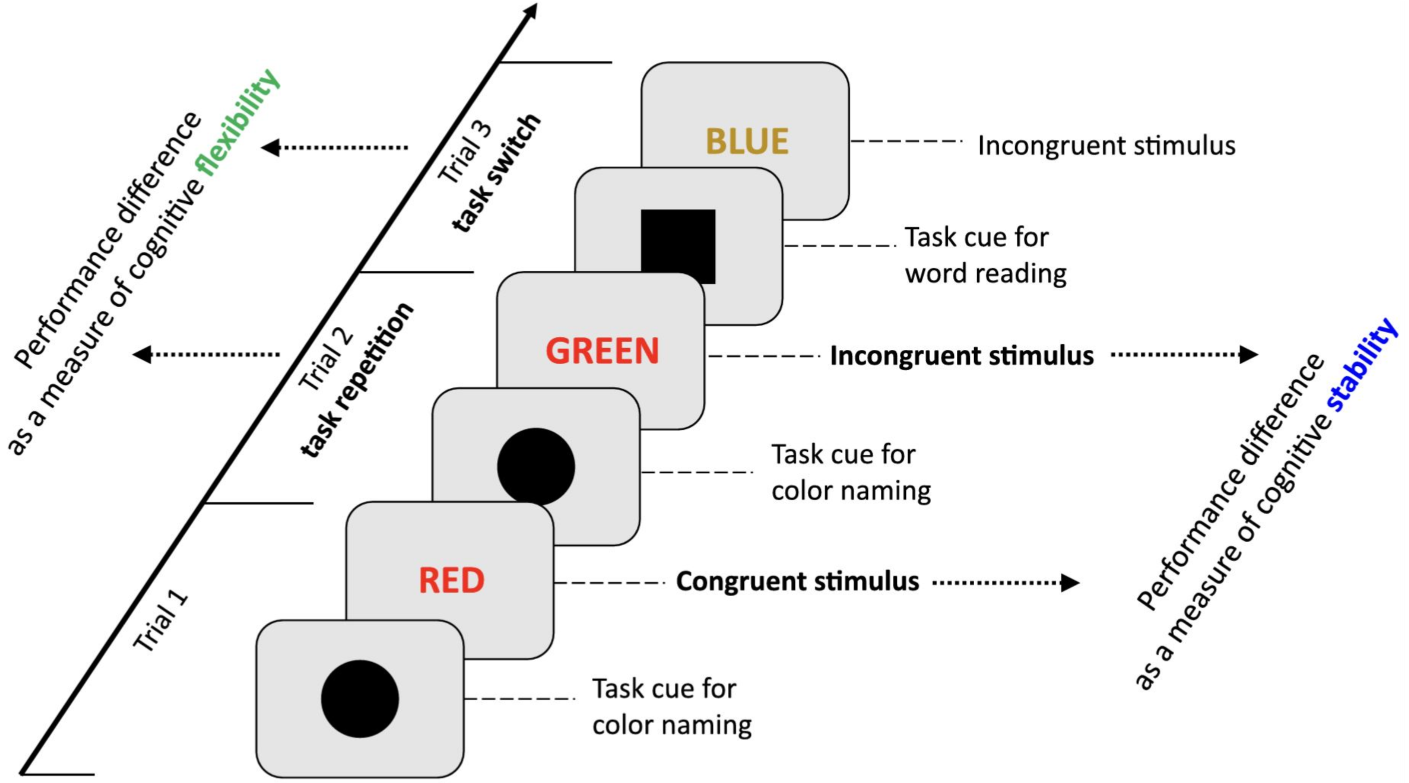


The **larger the congruent effect**
(Δ of error rate and/or reaction time),
the **lower cognitive stability**.

Empirical Measurement of Individual Stability & **Flexibility**



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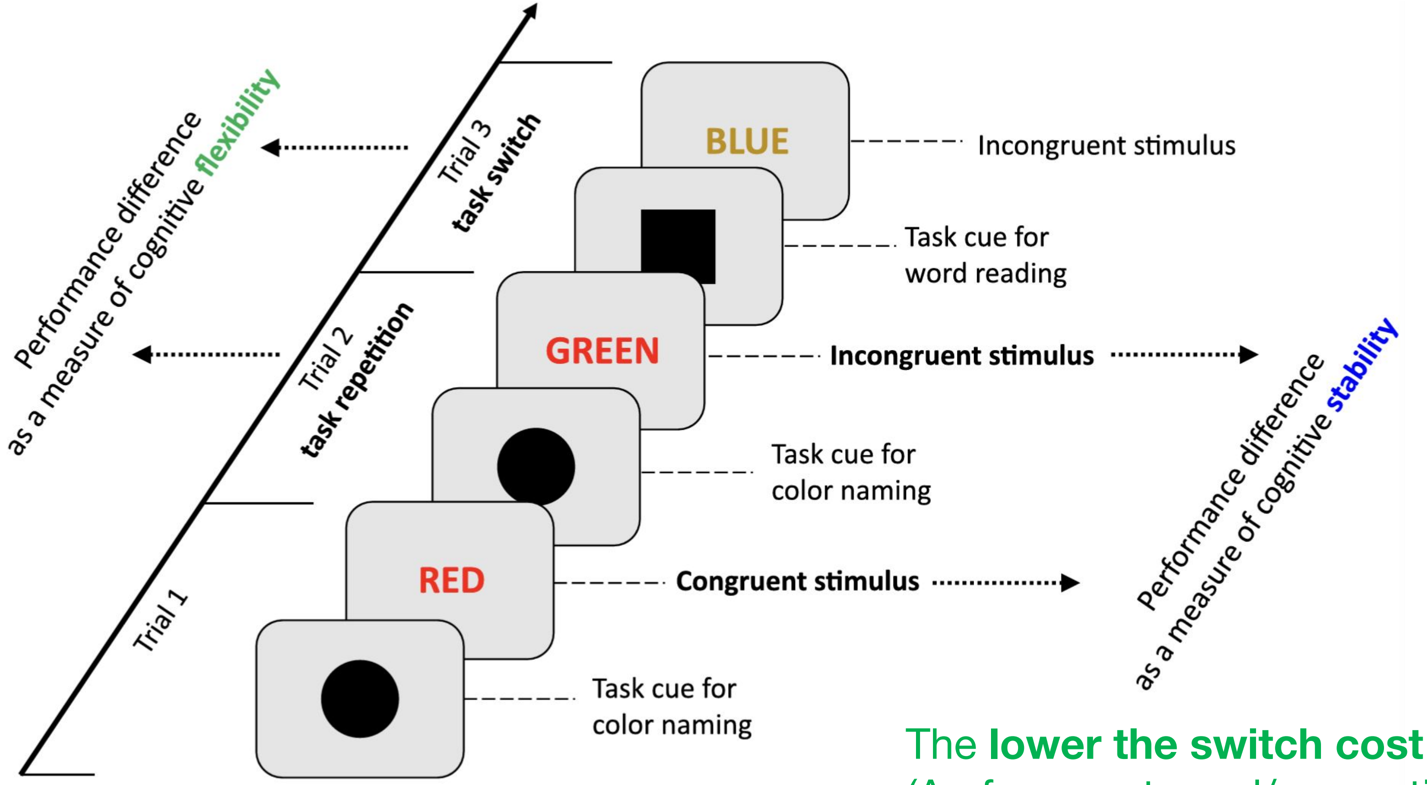
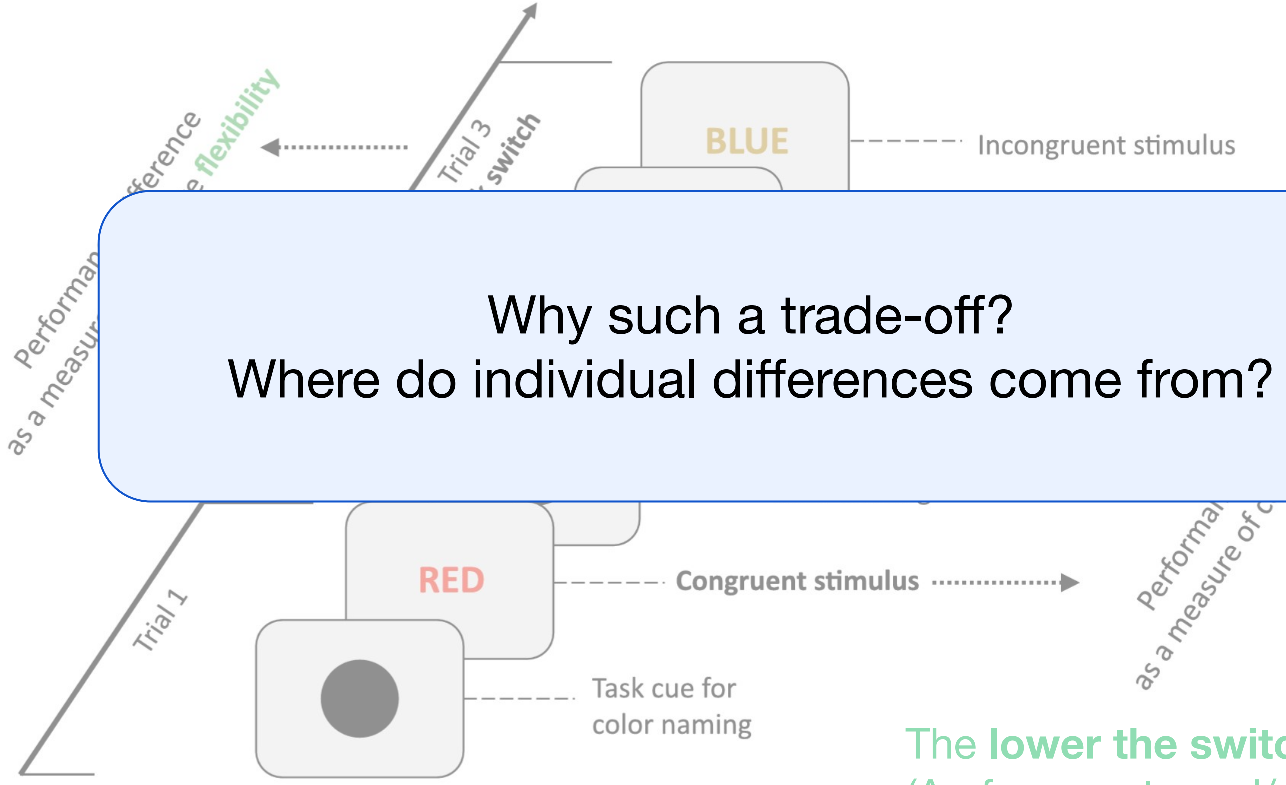


The **lower the switch cost**
(Δ of error rate and/or reaction time),
the **greater cognitive flexibility.**

Empirical Measurement of Individual Stability & **Flexibility**

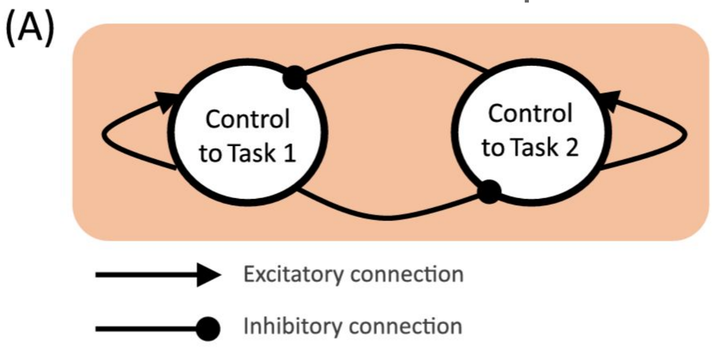


Why such a trade-off?
Where do individual differences come from?

The **lower the switch cost**
(Δ of error rate and/or reaction time),
the **greater cognitive flexibility.**

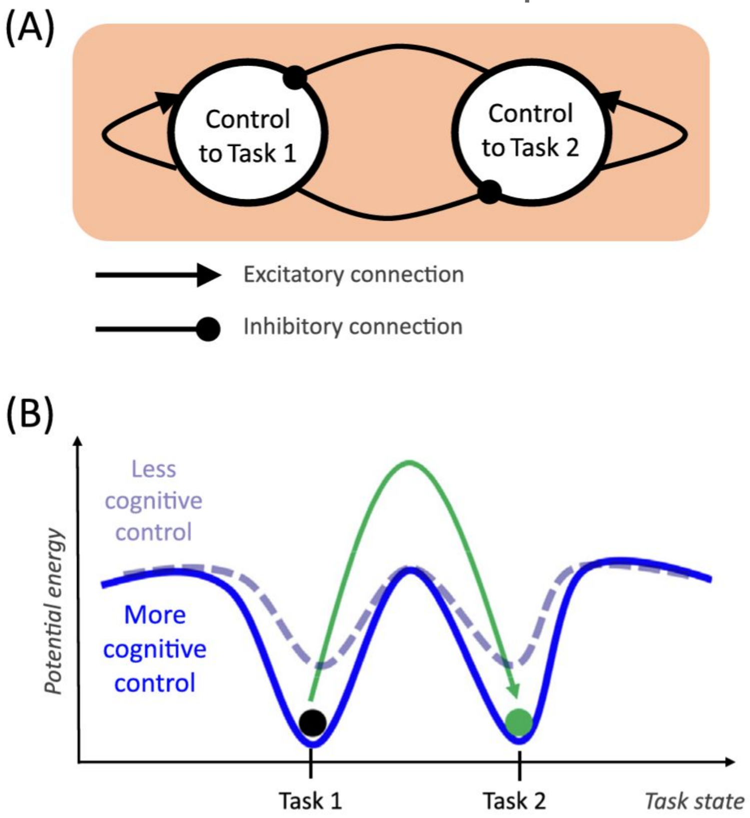
Computational Model

Each unit represents a control signal



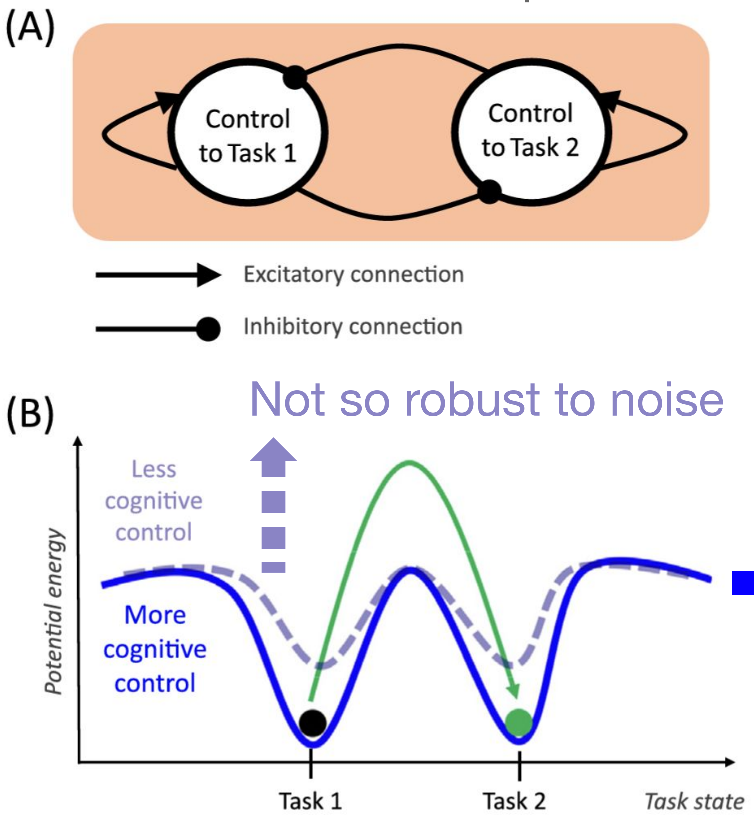
Computational Model

Each unit represents a control signal



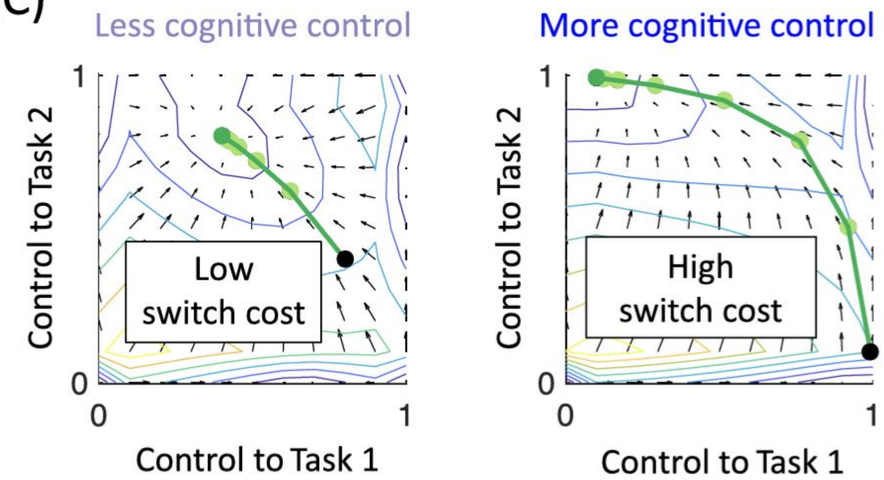
Computational Model

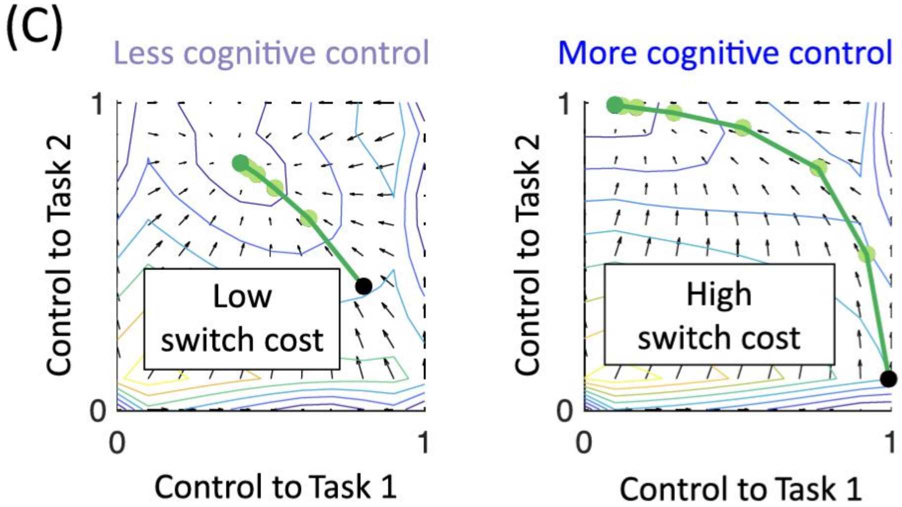
Each unit represents a control signal



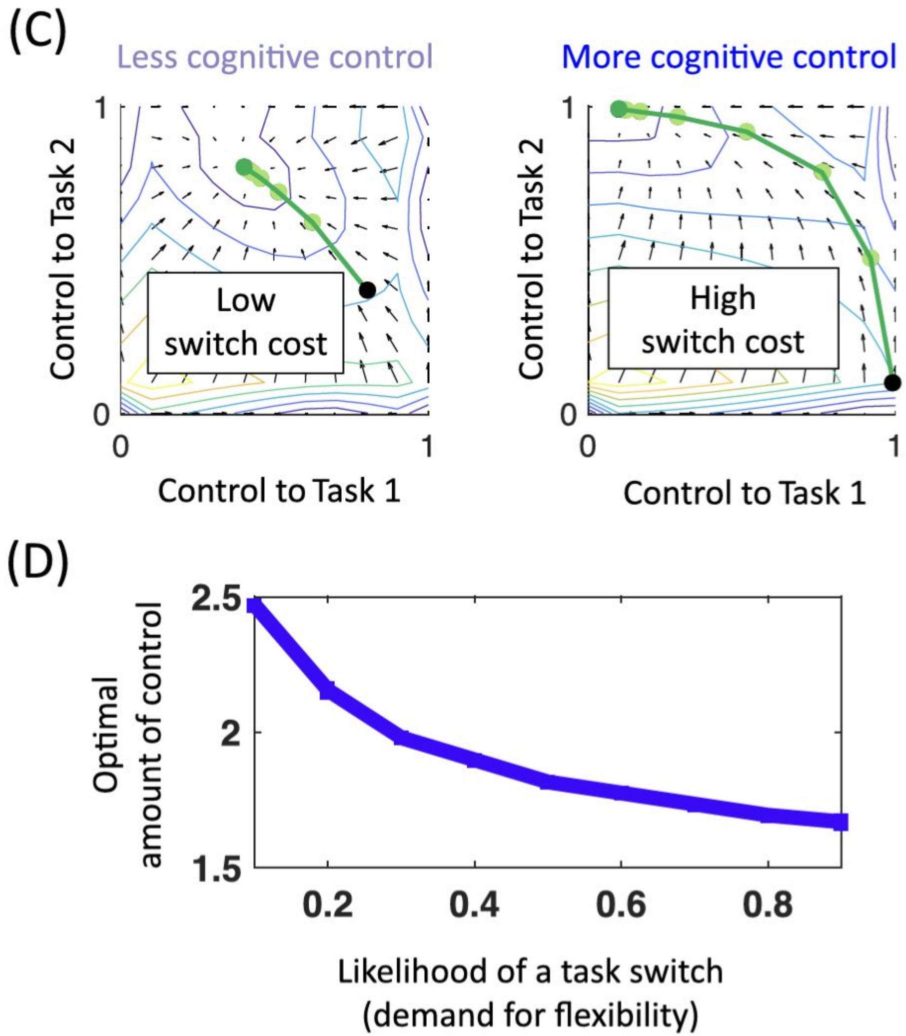
Robust to noise

(C)


Less cognitive control
More cognitive control
Low switch cost
High switch cost
Control to Task 2
Control to Task 1
0
1
0
1



Higher constraints on control allocation (shallower attractors) promote flexibility at the expense of robustness to distractors



(C)
Less cognitive control
More cognitive control
Control to Task 2
Control to Task 1
Low
switch cost
High
switch cost
0
1
0
1
(D)
Optimal
amount of control
2.5
2
1.5
0.2
0.4
0.6
0.8
Likelihood of a task switch
(demand for flexibility)

Conclusion

- Cognitive control limitations (multitasking & control intensity) arise from **shared representations** in neural systems.
- These constraints reflect two core computational trade-offs:
  - **Learning efficacy vs. processing efficiency**
    → Shared representations accelerate learning but impair multitasking.
  - **Cognitive stability vs. flexibility**
    → Shared representations enable task flexibility but require more control to avoid conflict and maintain task-specific focus.
- These trade-offs rationalize serial processing and control costs as **adaptive** (not flawed!) **features** of neural computation.

Future Directions

- Empirically test whether control-dependence reflects representational overlap;
- Identify neural substrates of shared resources via neuroimaging & electrophysiology;
- Investigate how practice & task training reduce interference via representation separation;
- Explore broader dilemmas (e.g., explore–exploit, effort–fatigue) as sources of control constraints.

Why do we get distracted?

Cognitive Effort: mediates between:

(1) our cognitive capacity to perform a certain task

(2) our *actual* performance on that task

Exerting cognitive effort is aversive!

- Why is cognitive effort aversive?
- How do we choose to invest cognitive effort?

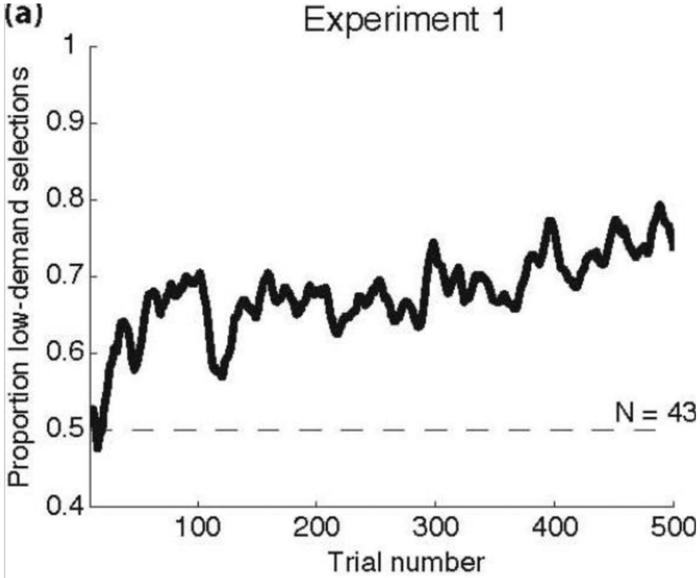
Toward a Rational and Mechanistic Account of Mental Effort

Amitai Shenhav,[1,2] Sebastian Musslick,[3] Falk Lieder,[4]
Wouter Kool,[5] Thomas L. Griffiths,[6]
Jonathan D. Cohen,[3,7] and Matthew M. Botvinick[8,9]

Cognitive effort is **aversive** and costly

"Demand selection task" paradigm *(Kool et al. 2010)*

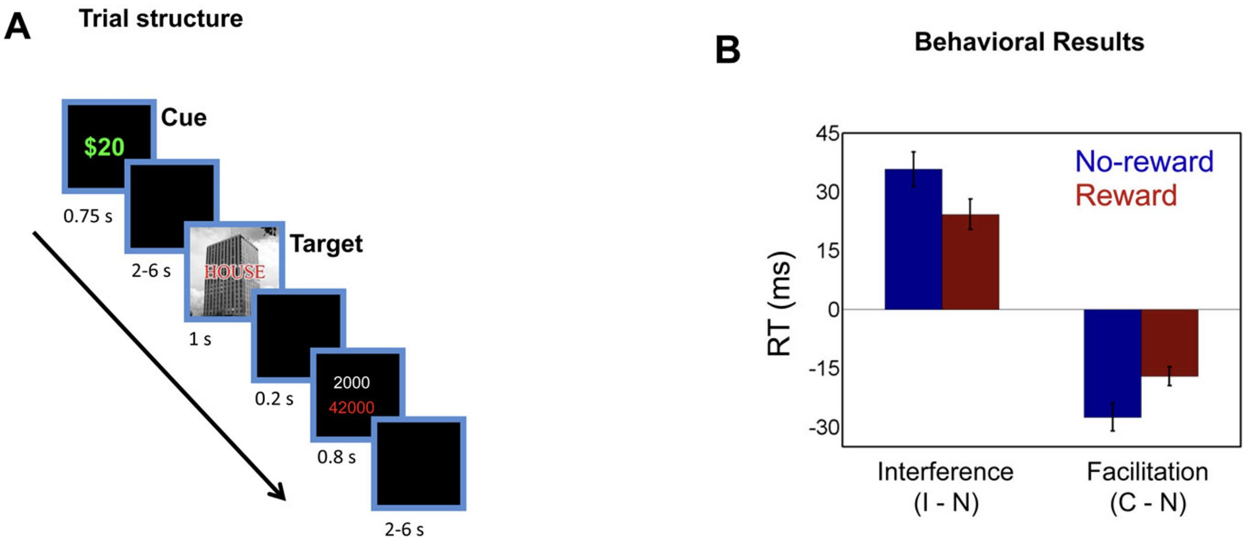
If the number is **blue**, respond if the number is less than 5.
If the number is **purple**, respond if the number is even.
One of the decks switches contexts more often!



Cognitive effort is aversive and **costly**

Reward can enhance attentional control…

…in a selective attention task *(Padmala and Pessoa 2011):*



Cognitive effort is aversive and costly

Reward can enhance attentional control…

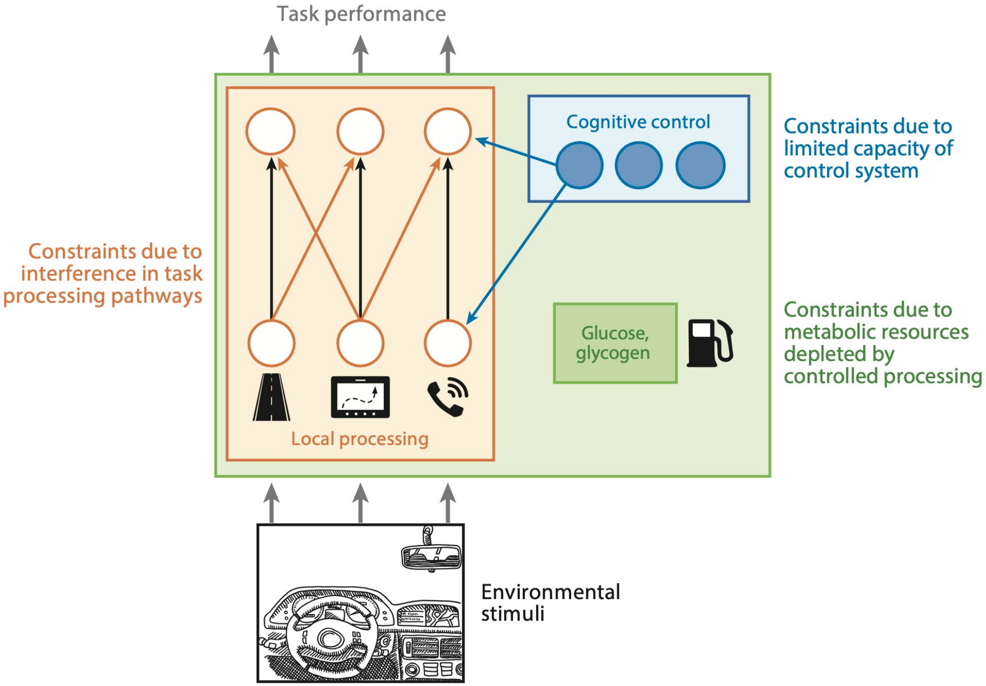
…in a selective attention task *(Padmala and Pessoa 2011)*

…in a Stroop task *(Krebs et al. 2010)*

…in a “task switching” paradigm *(Umemoto and Holroyd 2014)*

…on an intelligence test *(Duckworth et al. 2011)*

Cognitive effort may be aversive because it consumes a limited mental resource



Allocating mental resources to a task caries an opportunity cost of not being able to do other control - dependent tasks!

How does the brain allocate cognitive effort?

- We'd like to allocate mental effort in a way that *maximizes reward* while *minimizing cognitive effort.*
- How does the brain navigate this tradeoff?

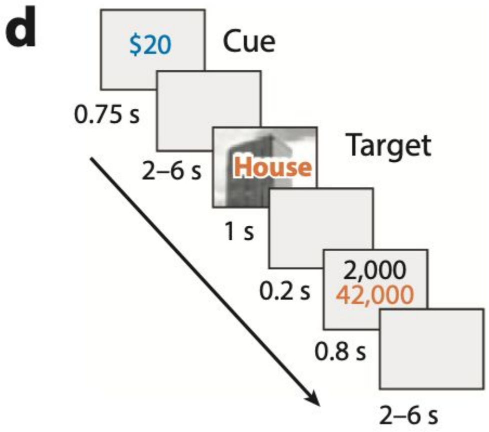
The “Expected Value of Control” framework formalizes the cognitive effort tradeoff

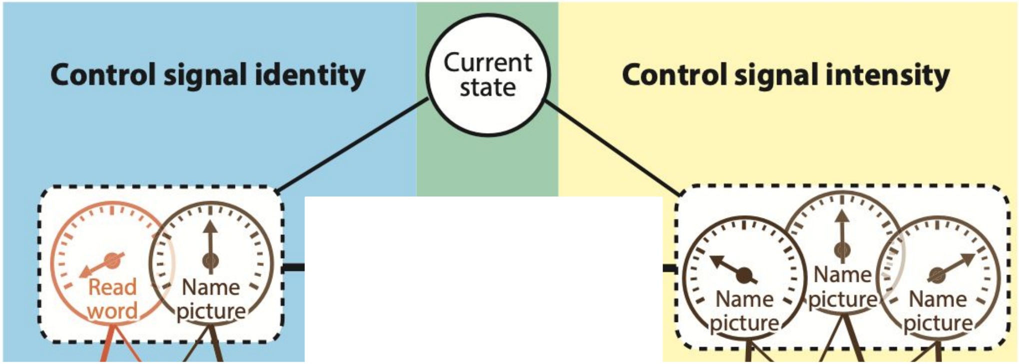
The ”value” (EVC) of a control signal is determined by:

1) The effect of the signal on the likelihood of obtaining reward

2) An inherent cost related to the intensity of the control signal

The “Expected Value of Control” framework formalizes the cognitive effort tradeoff





The “Expected Value of Control” framework formalizes the cognitive effort tradeoff

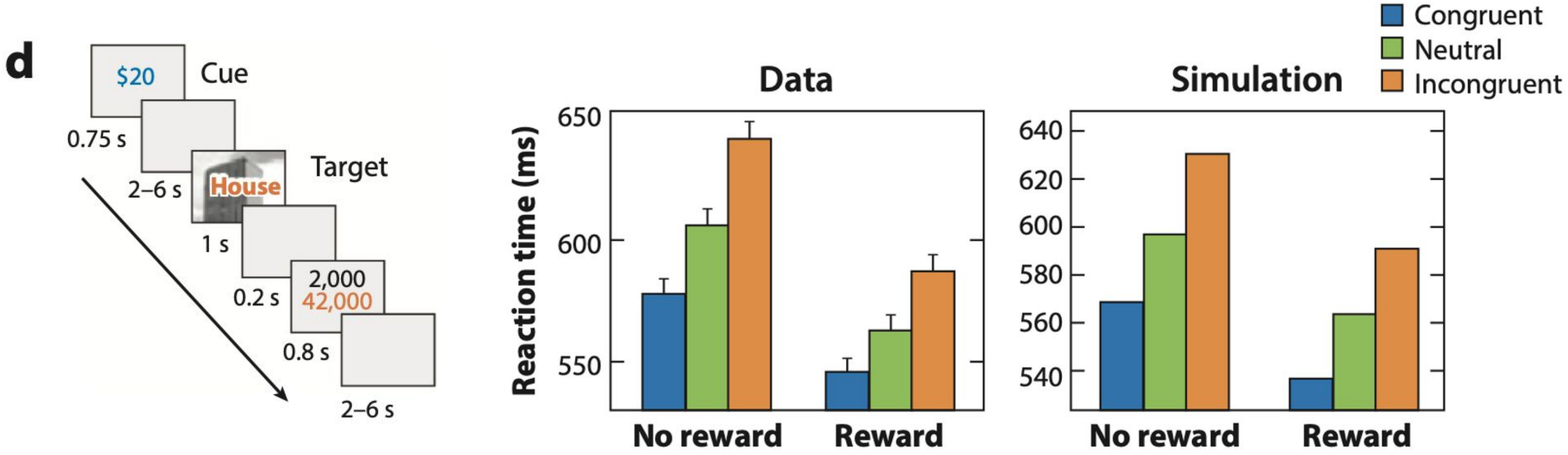
Formally, we define the EVC of a control signal in a state as:

$$\mathrm{EVC}(\mathrm{signal}, \mathrm{state}) = \left[\sum_i \mathbb{P}(\mathrm{outcome}_i | \mathrm{signal}, \mathrm{state}) V(\mathrm{outcome}_i) \right] - C(\mathrm{signal})$$

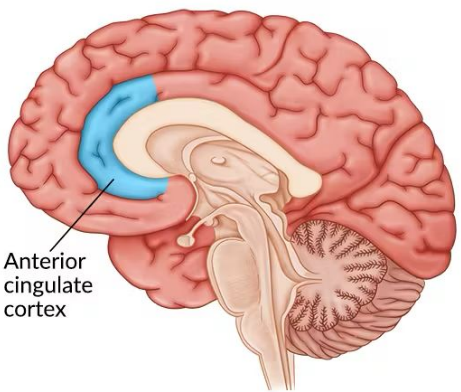
The “value” of a state is related to the expected future reward:

$$V(\mathrm{outcome}) = R(\mathrm{outcome}) + \gamma \max_i \mathrm{EVC}(\mathrm{signal}_i, \mathrm{outcome})$$

The “Expected Value of Control” framework formalizes the cognitive effort tradeoff



Dorsal anterior cingulate cortex may play a role in integrating signals relevant to the EVC



dACC activity…

- …tracks variables related to cognitive demand: e.g. errors, conflict, and surprise
- …encodes the values of potential outcomes
- …tracks subjects' aversion to expending cognitive effort
- …predicts future control adjustments
- …is related to *physical exertion*

Why do we get distracted?

Exerting cognitive effort is aversive because it consumes a limited cognitive resource.

The EVC theory is a quantitative framework to model the cost - benefit tradeoff in allocating effort.

dACC may be the neural substrate that performs this cost - benefit analysis.