On the Rational Boundedness of Cognitive Control

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Introduction

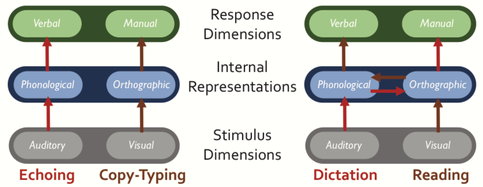
» Capacity for cognitive control is fundamentally limited (1,2)

» The bounds of controlled processing are
- a **defining feature** of cognitive control (1,2),
- a **premise** of general theories of cognition (e.g. ACT-R, 3),
- an **explanatory variable** in recent models of control allocation (4).

» A widely accepted view is that constraints in the capacity for controlled processing arise from structural limitations inherent to the control system itself.

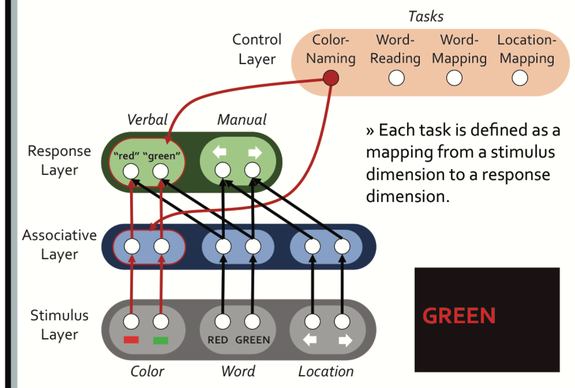
» We test an **alternative view:** Capacity limitations arise from shared representations between tasks (multiple-resource hypothesis, 5, 6, 7).

A demonstration of the multiple-resource hypothesis by Shaffer (1975)



Participants can learn to dual-task echoing and copy-typing but fail to dual-task dictation and reading.

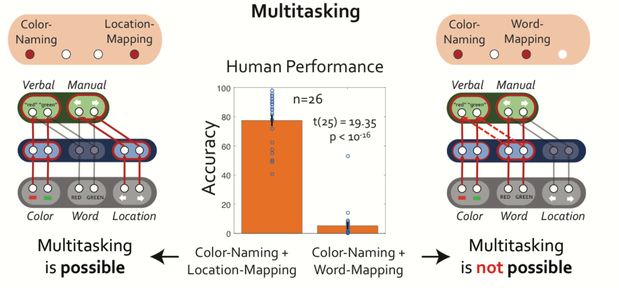
Extended Stroop Model



» Each task is defined as a mapping from a stimulus dimension to a response dimension.

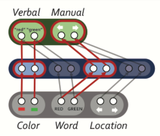
» The purpose of cognitive control is to prevent cross-talk by limiting the engagement of representations to a single task.

Multitasking



» Multitasking color-naming and word-mapping inadvertently engages the word reading pathway due to a shared representation with the word mapping pathway, introducing interference with the color naming task.

» Multitasking interference can be avoided by separting representations for words between tasks.



Graph Theoretic Analysis

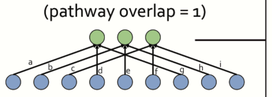
Bipartite Task Graph

Each **task** is defined as an edge between an input node (stimulus representation) and an output node (response representation).

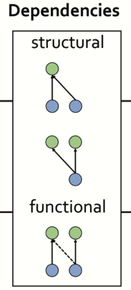
Pathway overlap is defined as the number of tasks that share the same stimulus representation.

Basis Set Representation (pathway overlap = 3)

Tensor Product Representation (pathway overlap = 1)

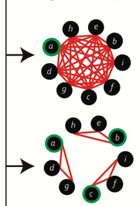


Task Dependencies



Dependency Graph

node => task
edge => dependency between 2 tasks

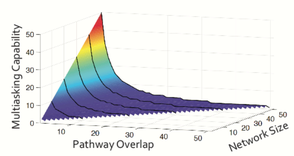


MIS = 1 (LOW multitasking capability)

MIS = 3 (HIGH multitasking capability)

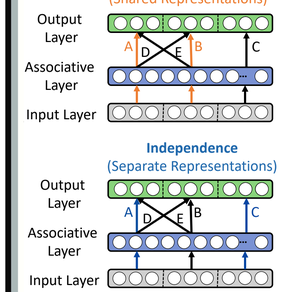
Multitasking Capability = Maximum Independent Set (MIS)

How does the multitasking capability of a network scale with the amount of pathway overlap?

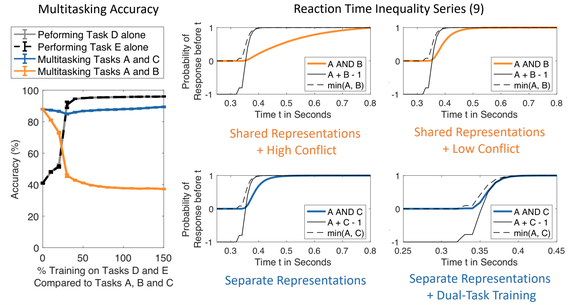


Shared representations drastically limit the multitasking capability of a neural architecture.

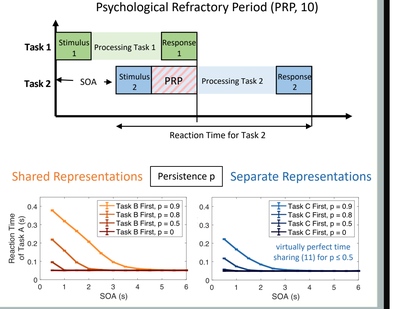
Shared Representation, Conflict and Persistence Constrain Multitasking Performance



Shared Representation & **Conflict**

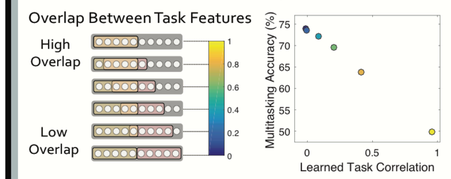


Shared Representation & **Persistence**



Tradeoff Between Learning Efficiency and Multitasking Capability

Extrinsic Biases Toward Shared Representation



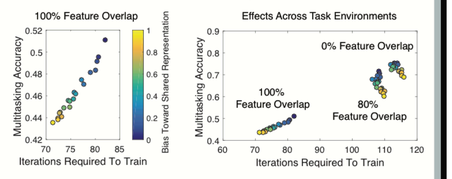
Shared representations (and constraints on multitasking) arise from high overlap between stimulus features of different tasks.

For linear networks it can be shown that:

$$\text{time required to learn all tasks} \sim \frac{\text{multitasking capability}}{\#\text{ of tasks relying on same stimulus features}}$$

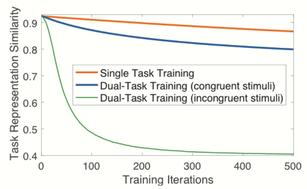
Multitasking limitations may reflect an optimal balance.

Intrinsic Biases Toward Shared Representation



Intrinsic biases for shared representation between tasks promote learning efficiency but constrain multitasking performance.

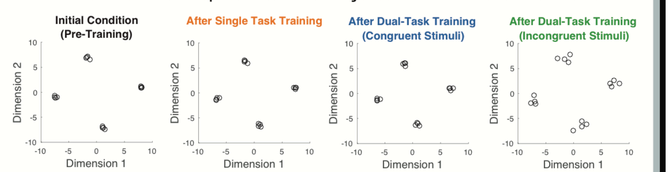
Overcoming Multitasking Limitations Through Pattern Separation



» Improvements in multitasking are accompanied by a separation of task representations.

» Pattern separation is strongest when tasks are trained (a) concurrently and (b) on stimuli that lead to response conflict.

Learned Task Representations Projected on 2-Dimensional Plane



Summary

» Shared representations between tasks limit multitasking performance.

» In this view, constraints in multitasking reflect the consequences of control doing its job, rather than limitations intrinsic to the mechanisms of control itself.

» Neural systems are subject to a fundamental tradeoff between learning efficiency and multitasking capability.

» Multitasking limitations can be overcome by separating representations between tasks.

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