A Neural Network Account of Binding Discrete Items Into Working Memory Using a Distributed Pool of Flexible Resources

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Abstract:

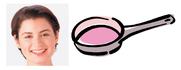
Recent data suggests that the information load of the number and complexity of objects in the memory set affects the quality of retrieval and the capacity of working memory.

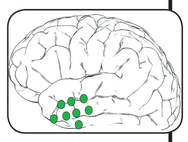
This suggests a pool of flexible resources which can be allocated as needed rather than a fixed number of slots. Our neural network model of flexible resources demonstrates how one can use localist representations for processing and representing information while distributed representations store the information.

We present the model as embedded in our Simultaneous Types/Serial Tokens model of visual working memory (Wyble & Bowman 2005, Bowman & Wyble In Prep).

Types

"A" "Cat"





Stimulus Specific

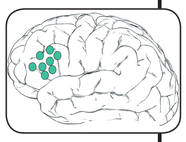
Only active during encoding and retrieval

IT Neurons of Desimone, Erickson & Miller 1996

Tokens

"Item one is ____"

"Item two is ____"



Stimulus non-specific

Sustain activity during WM maintenance

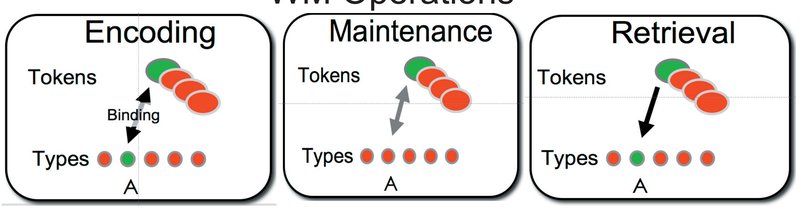
PF Neurons of Desimone, Erickson & Miller 1996

The Type/Token framework:

Allows the type network to process one item while others are being maintained

Encodes temporal order of WM contents

WM Operations

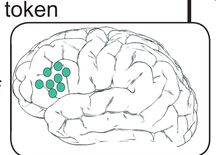


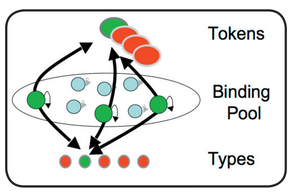
Binding

A separate pool of nodes stores these associations between types and tokens

This representation is distributed and forms a compact snapshot of activity in the entire set of type nodes separately for each token

The compact representation can store multiple snapshots of larger regions of cortex





These nodes are self excitatory and sustain activation during maintenance.

Encoding:

Activate a type and a token until N binding pool nodes are active

These N Binding Pool nodes will necessarily have strong connections to the type and token

These N Binding Pool nodes are a compact, distributed snapshot of the activity of the entire type layer

Multiple items can be encoded at the cost of degradation of all stored patterns

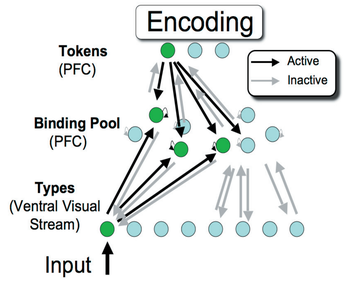
Model Implementation:

6 tokens
500 Binding Pool Nodes
3000 Type Nodes

Weights are random and never modiified.
Weights are equal in both directions

Token / Binding Pool Connection
Value randomly either 1.0 or 0

Type / Binding Pool Connection
Value randomly chosen from (0,1)



Retrieving a type:

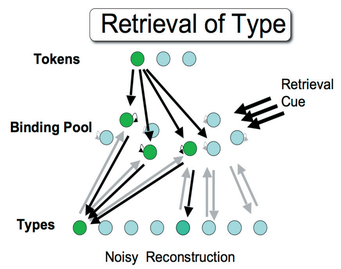
Activate a token with retrieval signal

The active Binding Pool nodes will reactivate the type(s) bound to that token

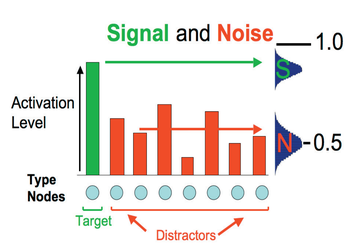
This reconstruction will be noisy

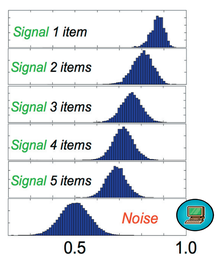
Retrieving a token:

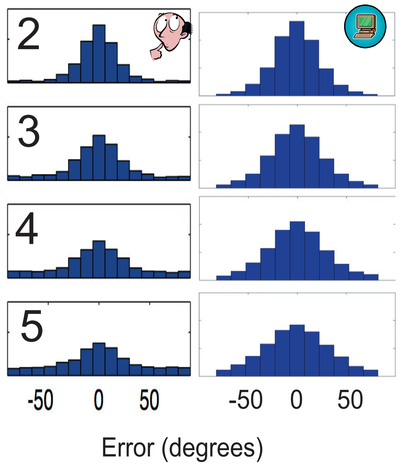
The same process works in reverse, activate a type to reactivate the token(s) it is bound to



Increasing Memory load Decreases Signal/Noise Separation
WM Capacity is reached when distributions overlap heavily







Noise increases with WM load

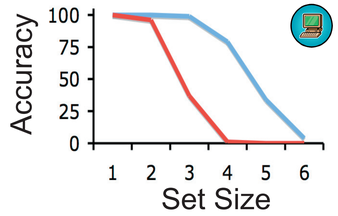
In simulation, recruiting additional Pool nodes reduces the strength of the signal distribution for each item

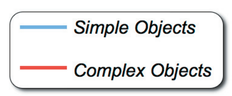
Interpreted as a population vector, the binding pool demonstrates a loss of fidelity as memory load increases

Human Data (left): error in recalling orientation of a gabor patch as set size increases from 2-5 (Wilken & Ma 2004)

Simulation (right): Type reactivation interpreted as a population vector as size increases from 2-5

Equation: Sum of Vectors (Rose Plot)





Information Load reduces WM capacity

WM Capacity is 3.7 for letters, 2.6 for icons and 2.0 for random shapes (Alvarez & Cavanagh, 2004)

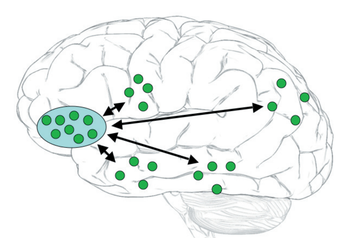
In the model, information load increases by activating 2 types per item instead of 1.

These less sparse patterns have lower signal/noise separation and consume more of the binding pool per item

Simulation: Cumulative probability of correctly retrieving all stored items from the memory set. # Types: 3000

$$P(h) = \int_0^1 s(x)\left(\int_0^x n(z)dz\right)^{\omega}\left(\int_0^x m(y)dy\right)^{\sigma-1}dx$$

s(x) = signal distribution
n(x) = noise distribution
m(x) = distractor distribution
P(h) = Probability of accurate recall
σ = Set Size
ω = Number of types - σ



A central bottleneck

A single binding pool in PFC should be able to store information represented in any cortical area, regardless of modality

A pool can bind multimodal percepts without resorting to synchrony

However, complex items must be bound sequentially

The attentional blink may result from a mechanism that enforces sequential encoding

References:
Wyble, B., & Bowman, H. (2005). Computational and experimental evaluation of the attentional blink: Testing the simultaneous type serial token model. Proceedings of the Annual Conference of the Cognitive Science Society.
Bowman, H., & Wyble, B. (In preparation). The Simultaneous Type, Serial Token Model of Temporal Attention and Working Memory.
Wilken & Ma (2004) A detection theory account of change detection. Journal of Vision 29(4) 1120-1135.
Alvarez & Cavanagh (2004) The capacity of visual short-term memory is set both by visual information load and by number of objects. Psychol. Sci. 15(2): 106-111