Neural architectures: what are they good for anyway?

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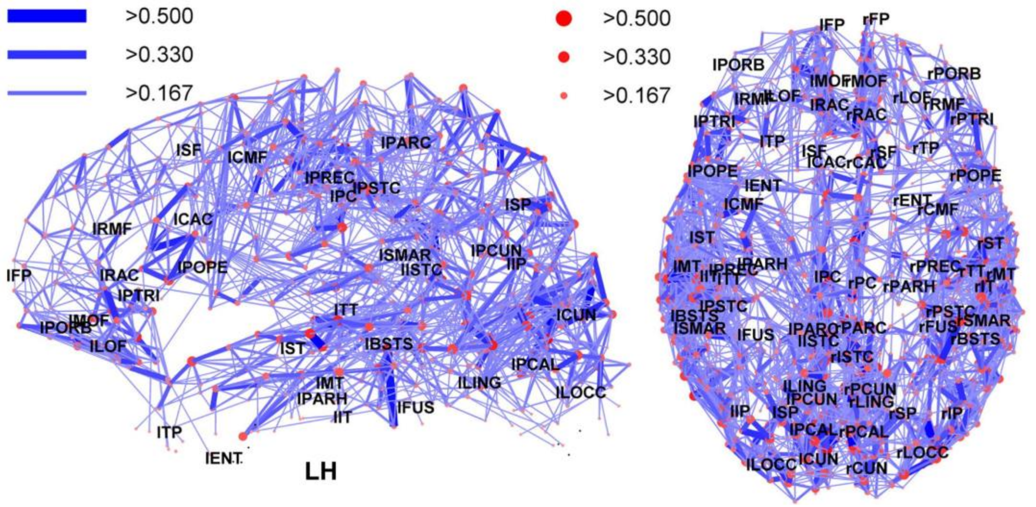
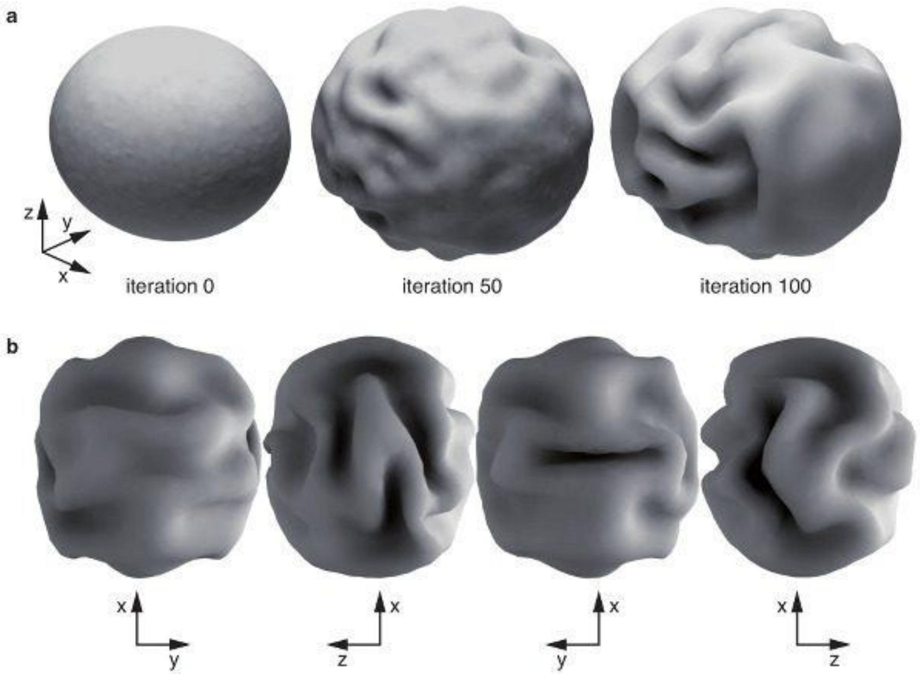
IMPERIAL

neural-reckoning.org

Why ask this question?

- Brain clearly has complex structure.
- We know that different brain regions have specific functions, e.g. language areas.
- On the other hand, you can rewire visual inputs to auditory cortex in a ferret, and it will learn to ‘see’ (Melchner et al. 2000).
- (Not very well though…)
- And if you believe Roberto Toro, all that complex brain folding shape can just be explained by the mechanics of a growing brain (Foubet et al. 2019).
- So maybe it doesn’t really mean anything?





How can we ask and answer this question?

What are some of the possible answers as to why the brain is structured the way it is?

- One possibility is that there is some necessary link between structure and function. The brain couldn’t do the things it needs to do if it had a different structure. Or a weaker version, it would do them less well.
- Maybe the system just happened to evolve that way (exaptation) but could equally well have been different.
- Causal effects may be complicated (e.g. you need areas A or B to do task X; or you need areas A and B)

All of this is tricky to establish.

The parable of the missing chalk

Suppose we asked: what makes for a good lecture?

Imagine a mathematician at a blackboard.

Take away her chalk and give her a whiteboard pen. The students don't follow her lecture.

⇒ So the chalk was key.

(Aside: many mathematicians believe this. I'm allowed to say this because I am one.)

This is a trivial example, but there are neuroscience papers today that do exactly this.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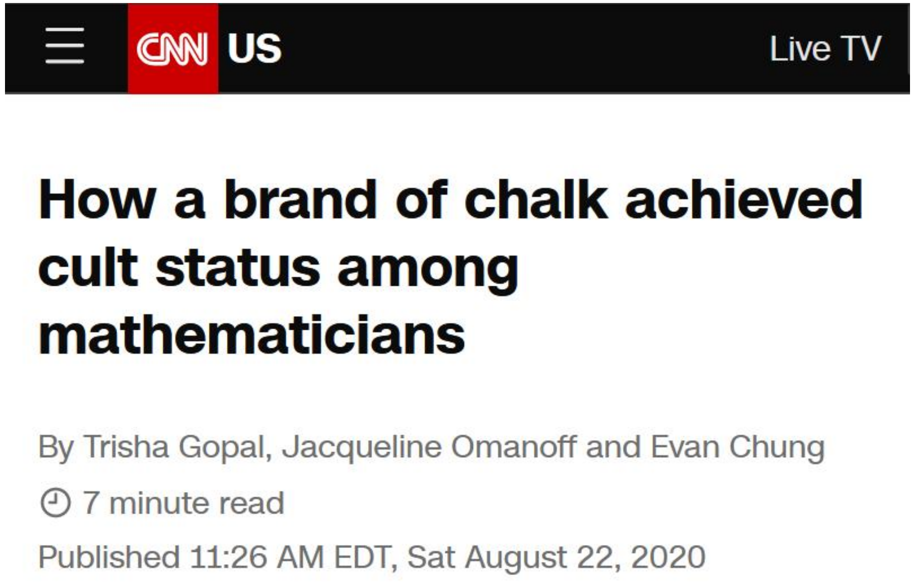
Tech

Hagoromo chalk: Why the demise of a Japanese company is a blow to mathematics

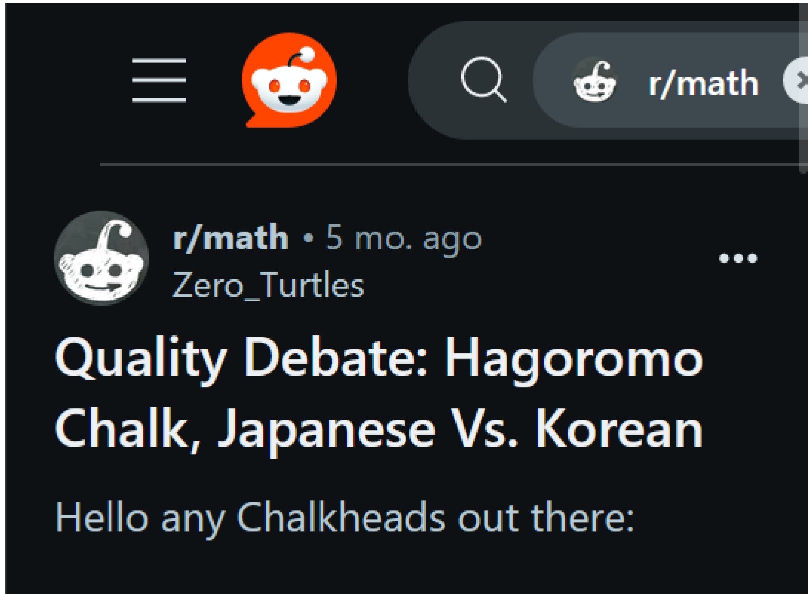

CNN US Live TV

How a brand of chalk achieved cult status among mathematicians

By Trisha Gopal, Jacqueline Omanoff and Evan Chung

7 minute read

Published 11:26 AM EDT, Sat August 22, 2020


r/math

r/math • 5 mo. ago

Zero_Turtles

Quality Debate: Hagoromo Chalk, Japanese Vs. Korean

Hello any Chalkheads out there:

Theory comes to the rescue

Resolution of the chalk experiment:

If we also replace blackboard with whiteboard the students now understand.

Experimentally, we can’t always do this! However, with models we can.

Simple prototype (it can be more complicated – don’t say the words “causal inference”):

Compare best possible performance at task T with and without architectural feature F, allowing other parameters and features of the model to vary.

Theory is essential in neuroscience because
there are questions we cannot answer with experiments.

We need to be careful to give equal attention to model with/without F. This is hard to do!

Computationally demanding: comparing best possible means big parameter sweeps

Modern machine learning methods help. We can finally do this properly.

(Or the old-fashioned way: sometimes we can analytically solve for optimal performance.)

Modularity: structure and function

Gabriel Béna
PhD student 2021-

Béna and Goodman (2025)
Nature Comms

TL;DR version of this study

Evidence:

Brain is "structurally modular"

Knocking out brain regions seems to lead to functional deficits

So…?

Functional specialisations a necessary consequence of structural modules?

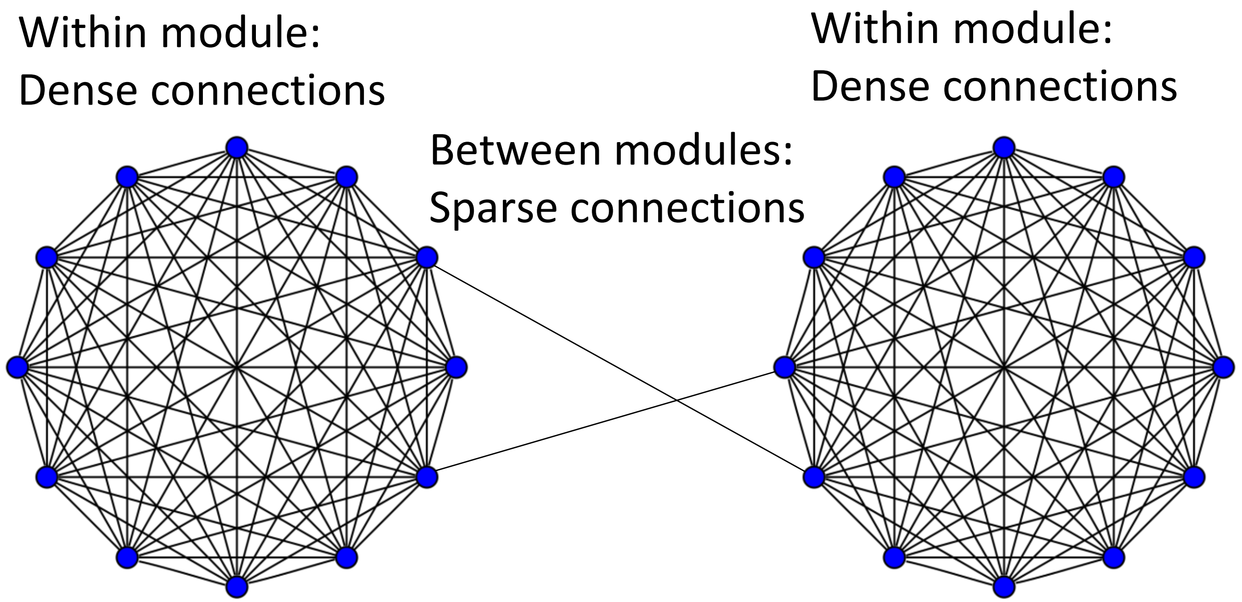
We tested this using ANNs

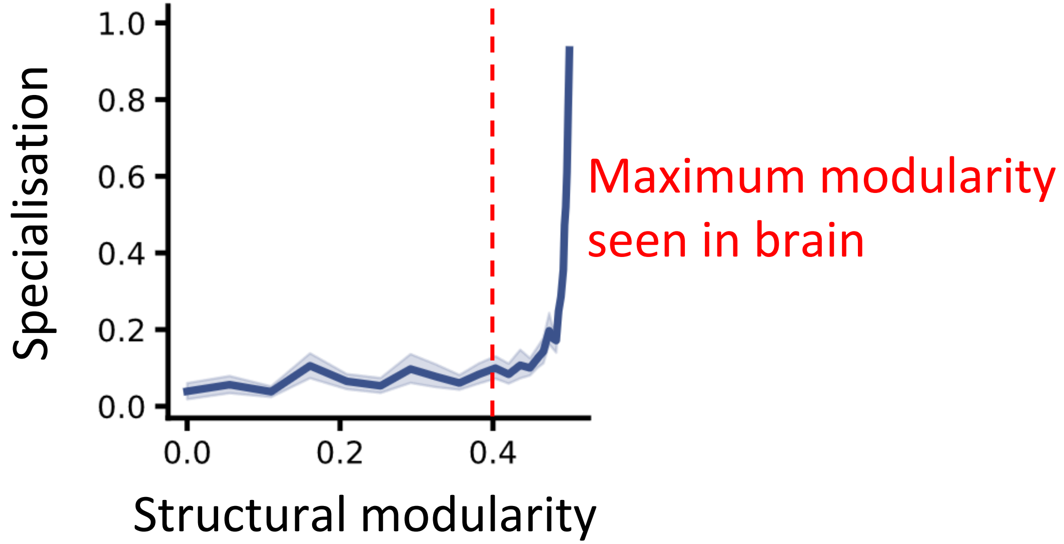
Answer is not necessarily.

At least, for levels of modularity in brain.

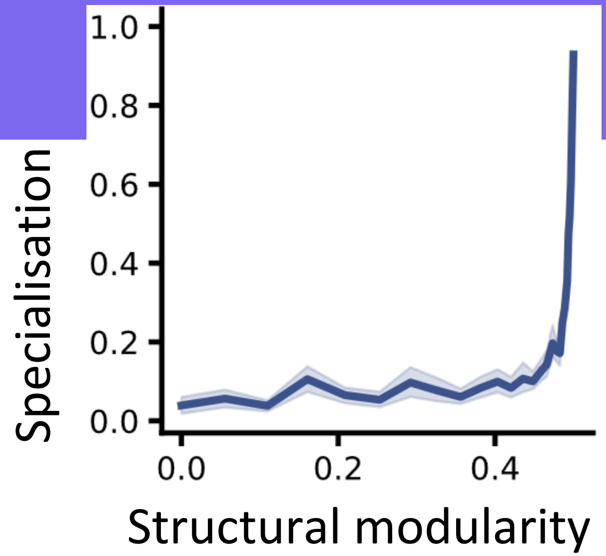
Also need tight resource constraints?

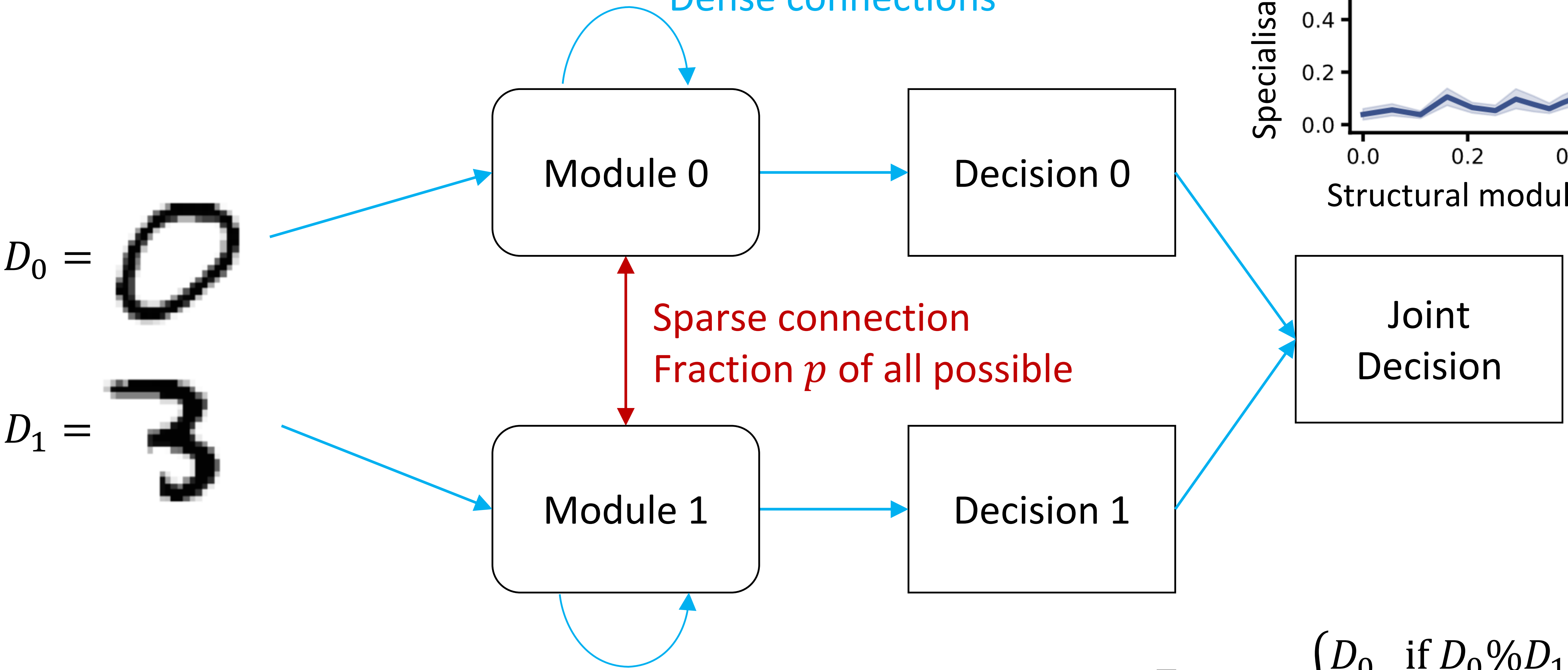
Interesting temporal dynamics.





Task and model setup

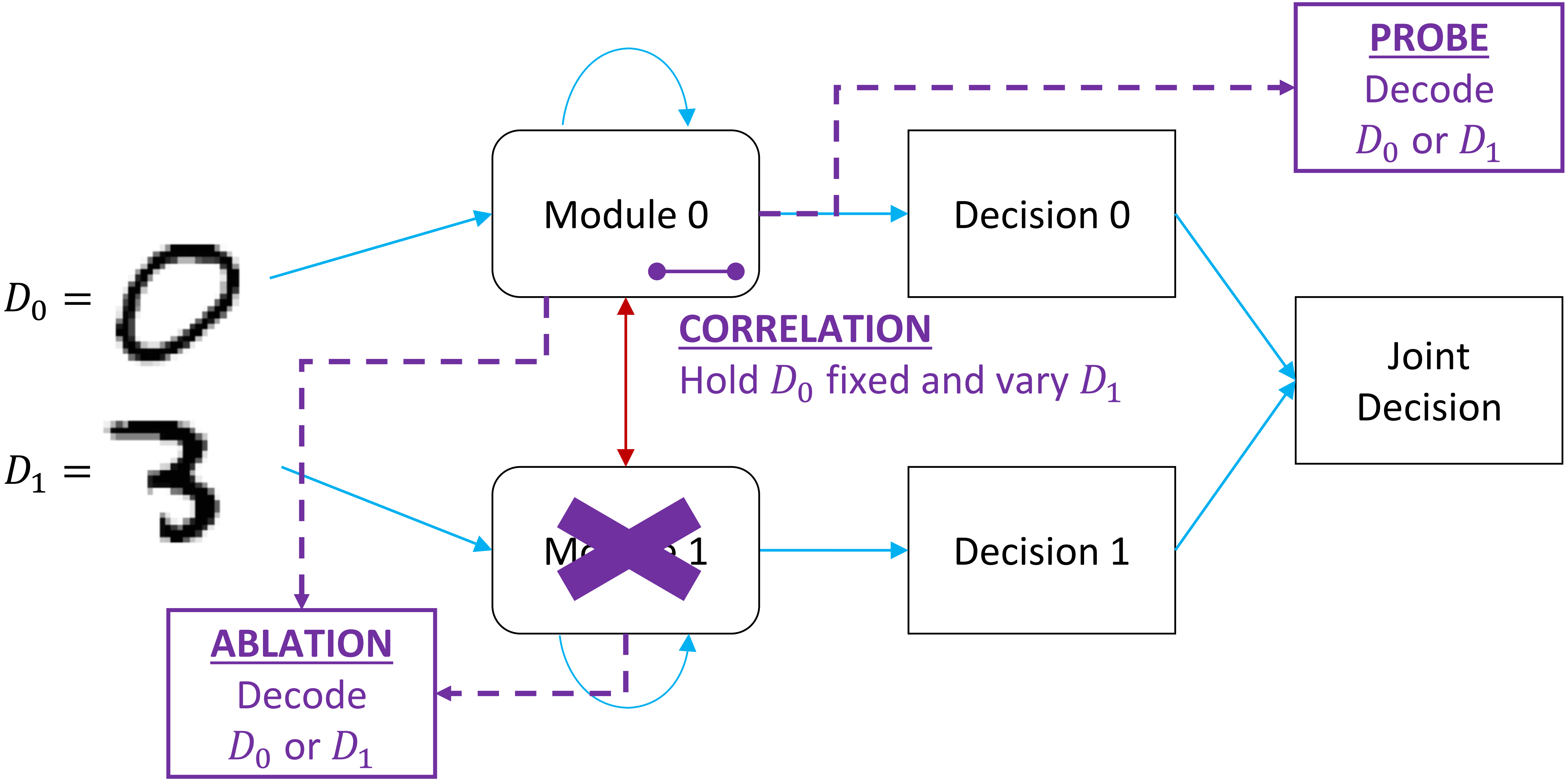




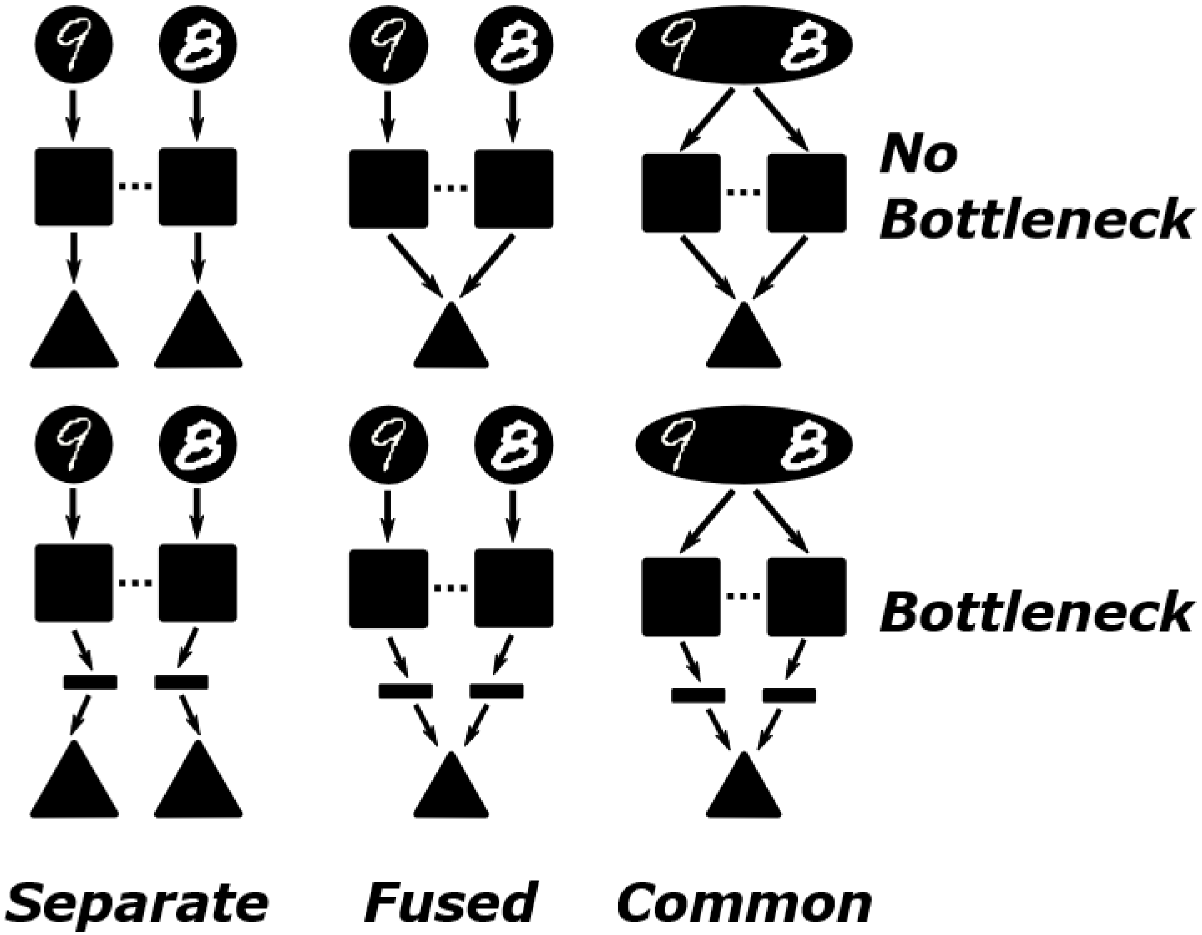
Note: structural modularity measured by $Q = \frac{1}{2} \cdot \frac{1-p}{1+p}$

Target = $\begin{cases} D_0 & \text{if } D_0 \% D_1 = 0 \\ D_1 & \text{if } D_0 \% D_1 = 1 \end{cases}$

Measuring functional specialisation



Model variants

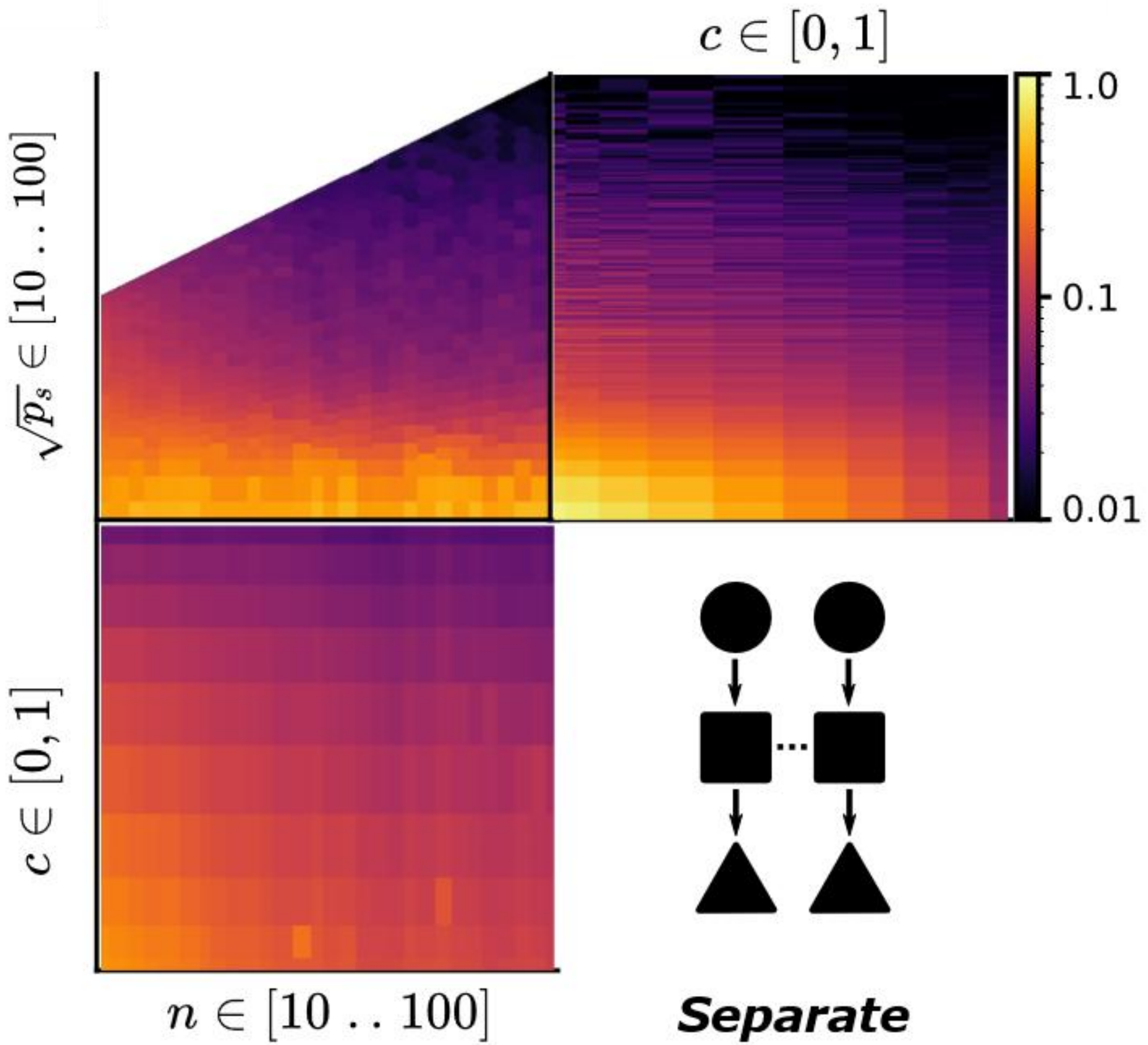


6 variants on this model

Separate pathways
Fused output pathway
Common input and output

In each case, with and without bottleneck

Detailed results



Varied parameters:

- c – correlation between input digits
- n – number of neurons in module
- p_s - number of inter-module synapses

Summary:

- Modularity can only emerge when task statistics are separable.
- When resources $(n, \mathrm{p_s})$ are low, modularity more likely.
- Depends on architecture, but similar pattern for the others.

Specialisation is transient

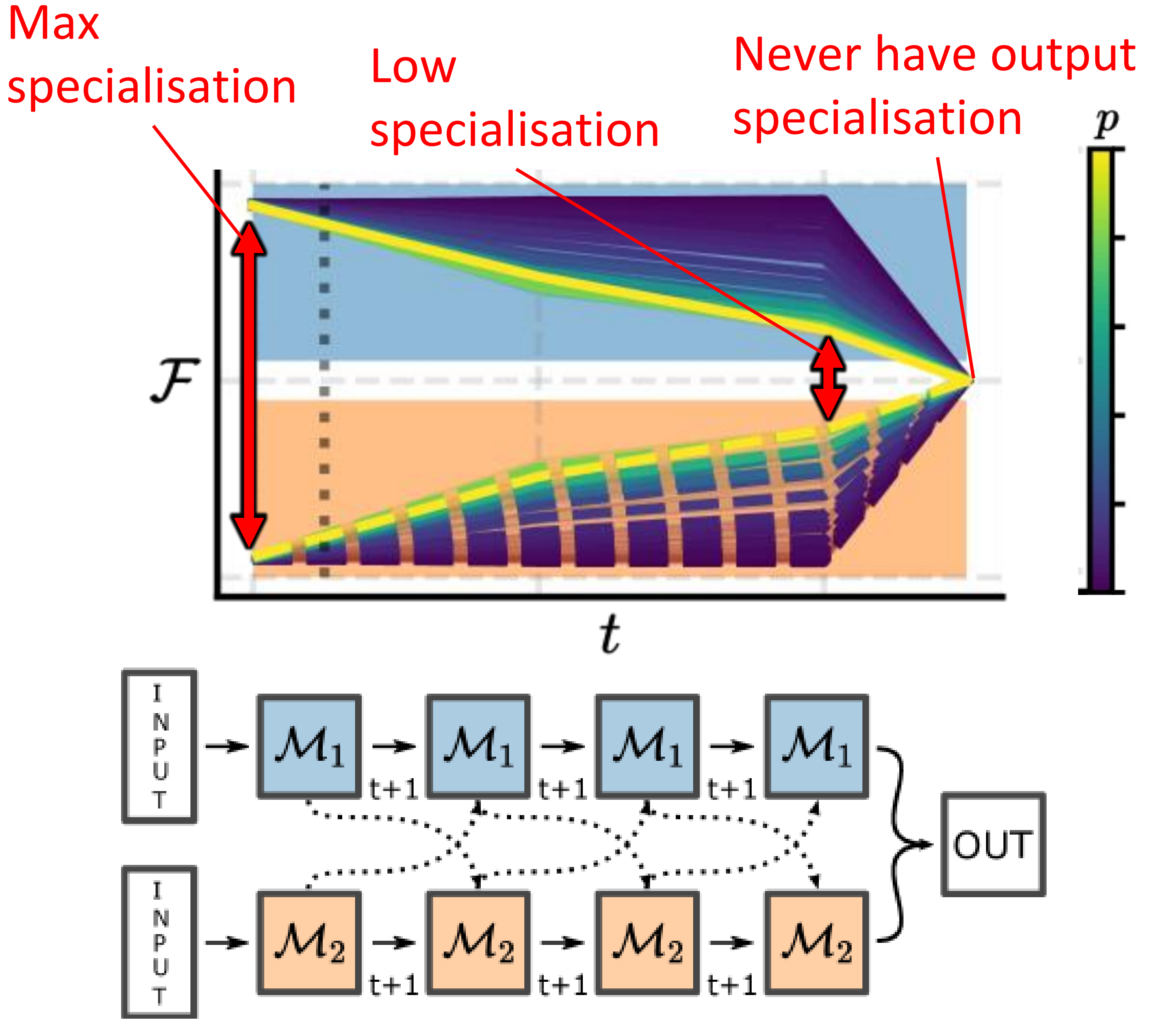
Specialisation decreases over time.

- Decreases slower with sparse connectivity.
- Decreases slower with noisy signals.

Suggests communication bandwidth is key.

Should we be looking for neural signatures of…?

- Transient specialisation
- Ongoing integration
- Multiple timescales of integration



Conclusions

The role of the observed structural modularity in the brain is not to guarantee functional modularity.

However, that doesn't mean they must be unrelated! We know they are.

But, we need more than just the structure to get that.

Resource constraints is one possibility.

But there may be others:

Learning rules. Environments (e.g. multi-task learning).

Training regimes. Architectures.

There seem to be interesting temporal dynamics to specialisation.

- We need better analytical tools to think about this.

All of our measures of specialisation can be experimentally measured.

Multimodal architectures

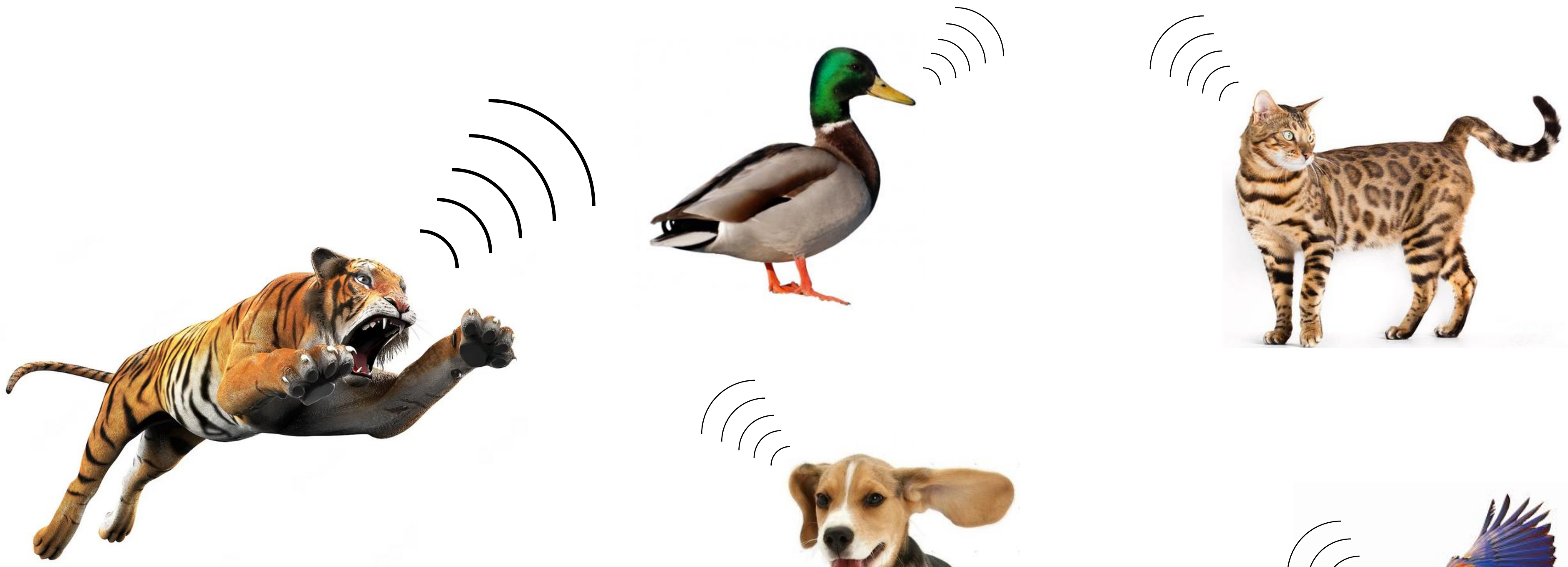
Marcus Ghosh
Postdoc fellow 2021-

Ghosh, Béna, Bormuth and Goodman (2024)
PLOS CB

Swathi Anil
Visiting PhD (2024)

Anil, Ghosh and Goodman (2024)
Preprint

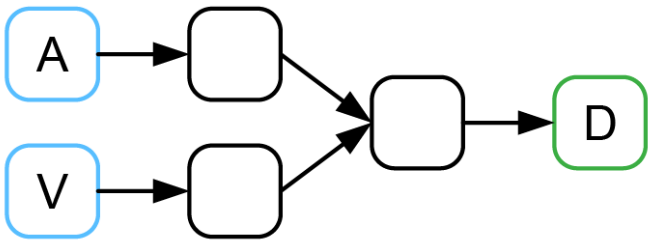
Q: optimal architectures for multimodal sensing…?



Cluttered audio-visual environment
Detect direction of object of interest
Use information from both audio and video
Task: target object moving left/right, background noise

Dan in his happy place says “let’s try a spiking neural network”

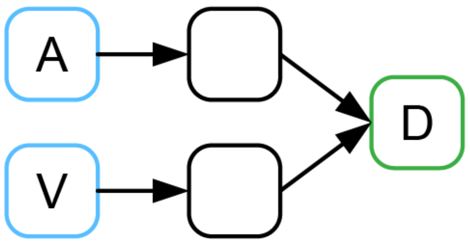
Multisensory



93% correct

It works!
Let’s just run a control…

Unisensory



93% correct

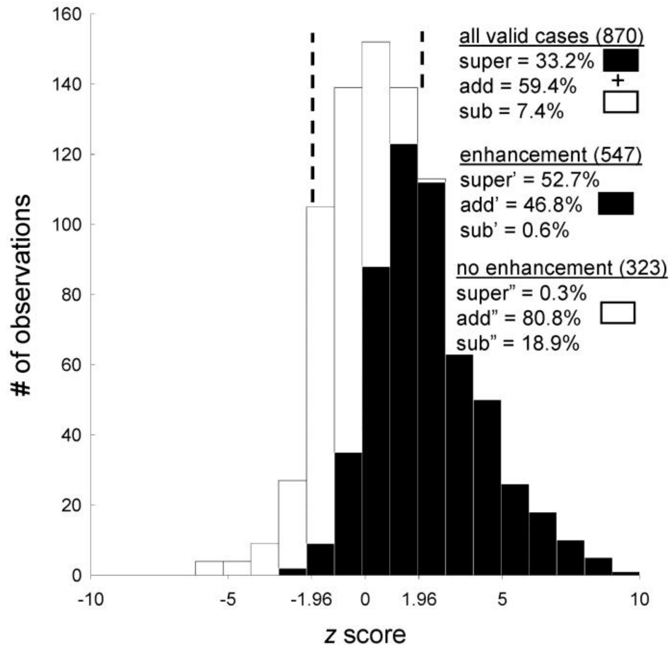
Wait… we can do the task without a multisensory area?

Do a little Bayes… optimal solution is linear

$$\log P(direction \mid observations) \propto$$
$$\textstyle\sum_t \log P(A_t \mid dirn) + \sum_t \log P(V_t \mid dirn)$$

$\Longrightarrow$ Readout neurons are enough

Stanford et al. 2005



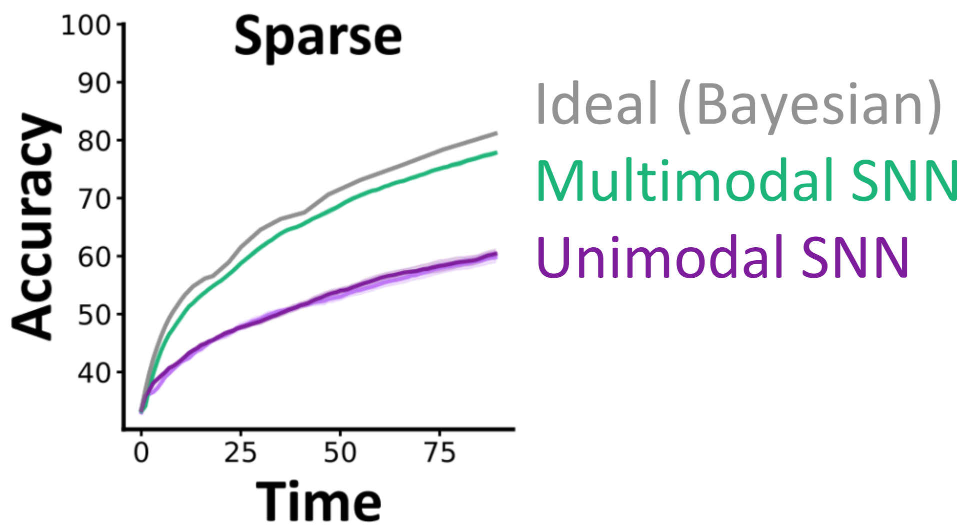
But we know there are multisensory areas with nonlinear neurons.

So what are they for?

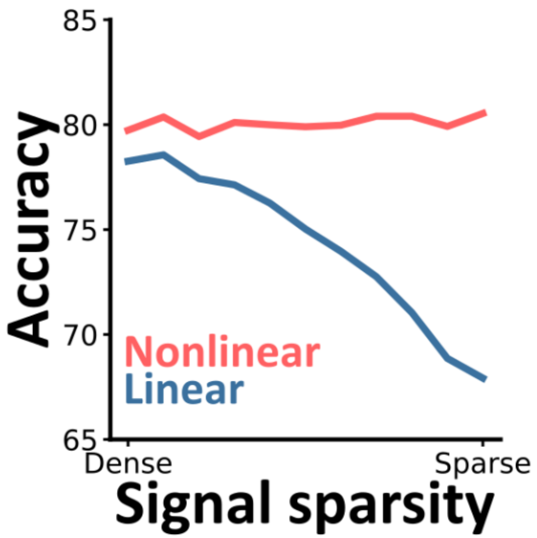
Prey detection task

Classic multimodal task with one slight tweak: Target emits signals at unknown times.

Clear advantage to have a nonlinear multimodal area.



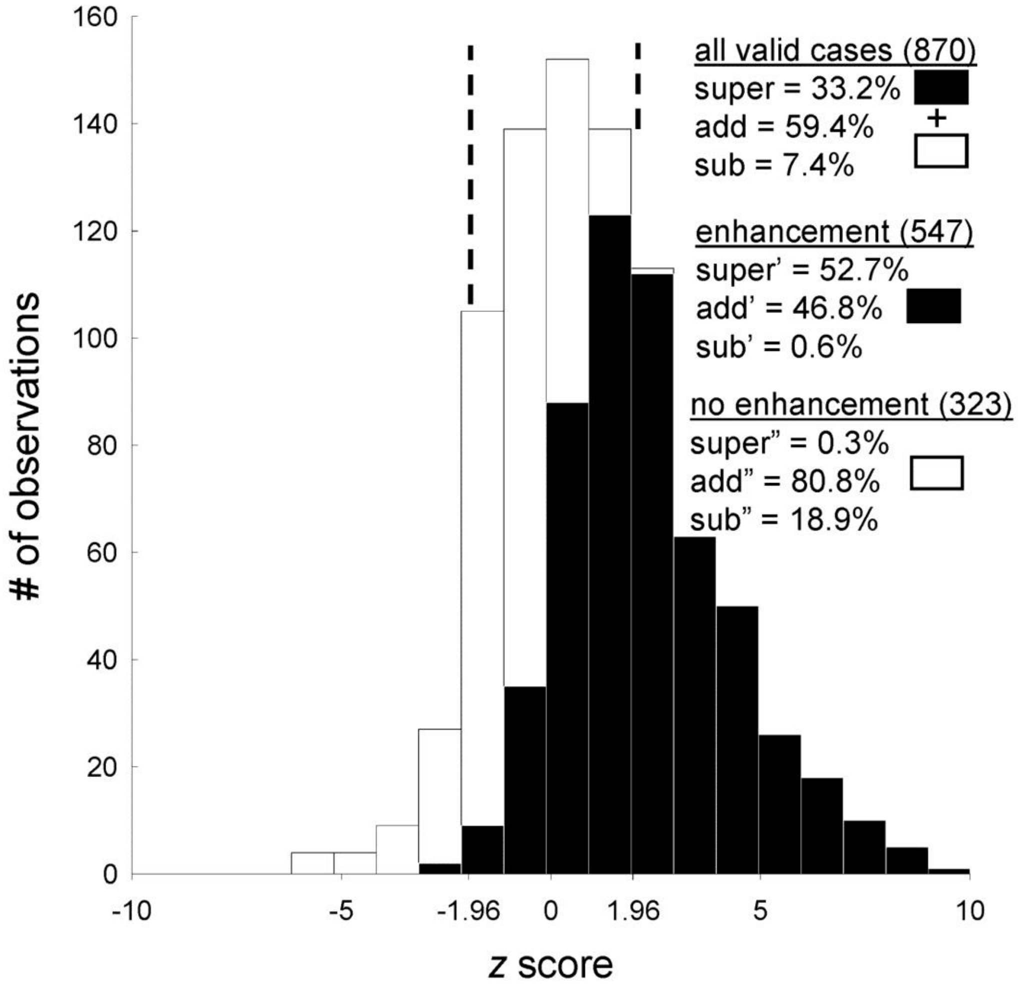
Advantage larger for sparser signals.



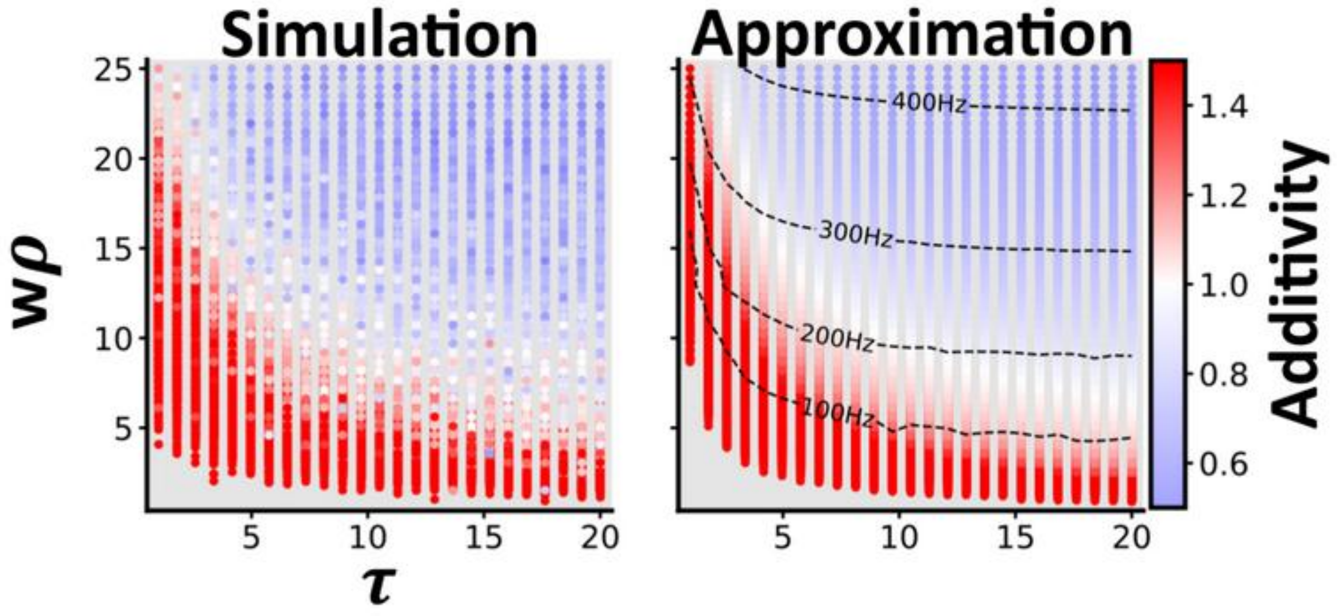
So does this explain the experimental data?

Can we explain this?

Stanford et al. 2005



Yes, but it doesn't depend on our model



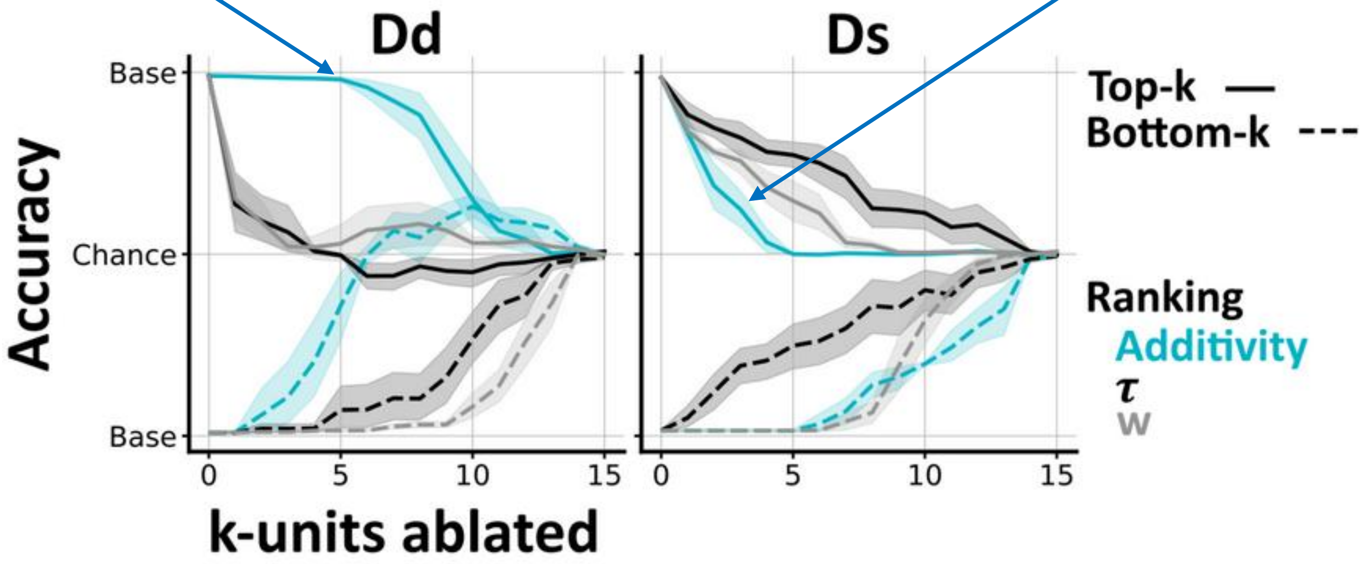
Could we test this experimentally?

Idea: ablations

Haven’t done the experiment yet, but our models suggest this should work

Removing superadditive units has little effect on task with dense signals (classical task)

But it has a big effect on the task when the signal is sparse (our new task)

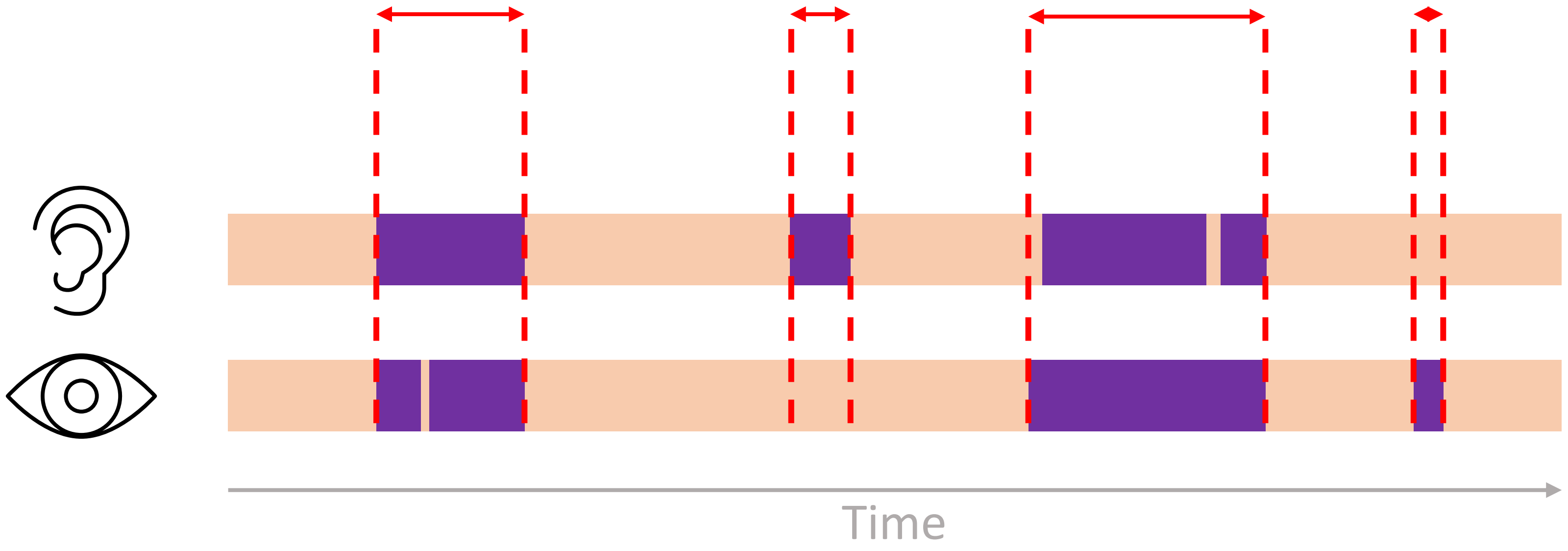


Follow-up: increasing time complexity

Swathi Anil

Marcus Ghosh

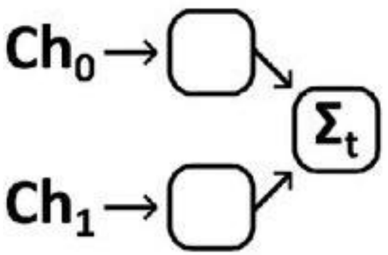
Information is **sparse** but arrives in bursts and is correlated across modalities



Background noise

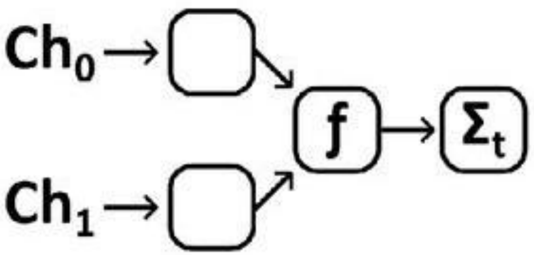
Signal

Linear fusion



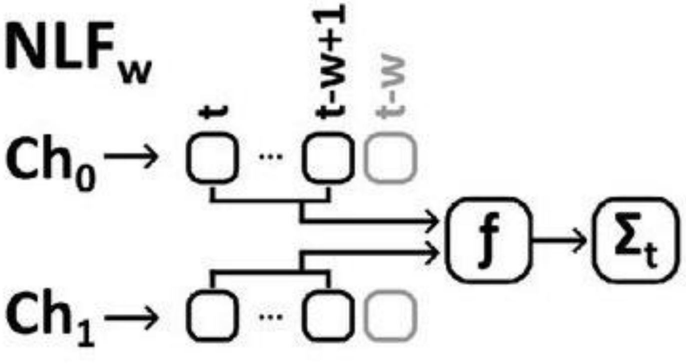
6 params

Nonlinear fusion



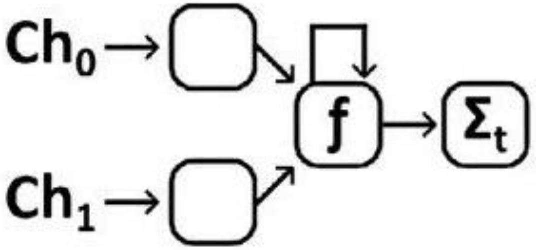
9 params

NLF_w



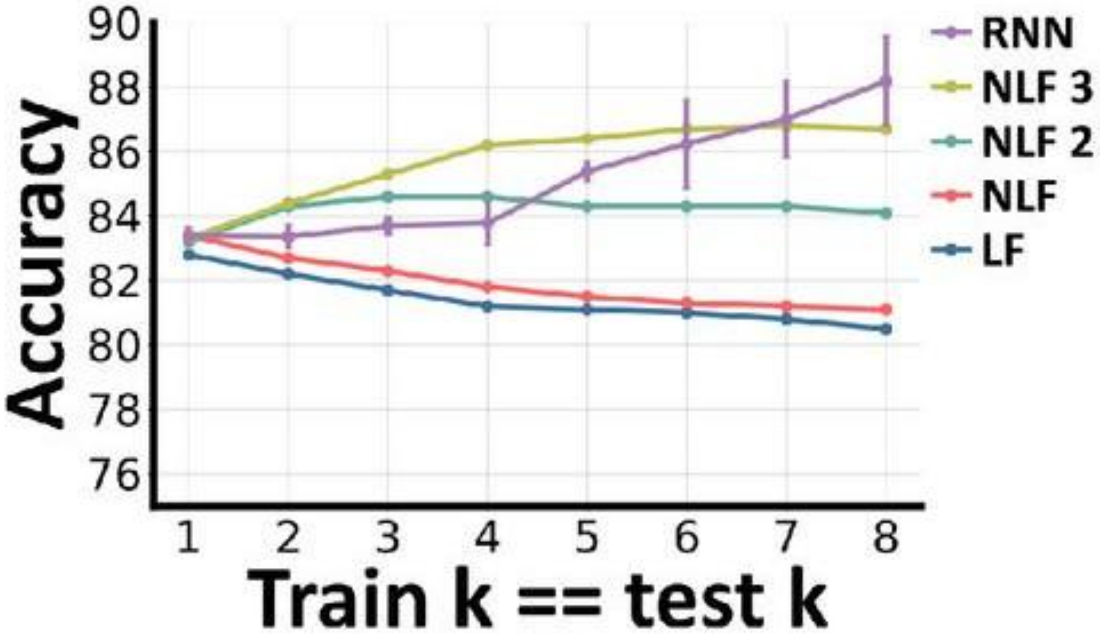
81 to 729 params

RNN

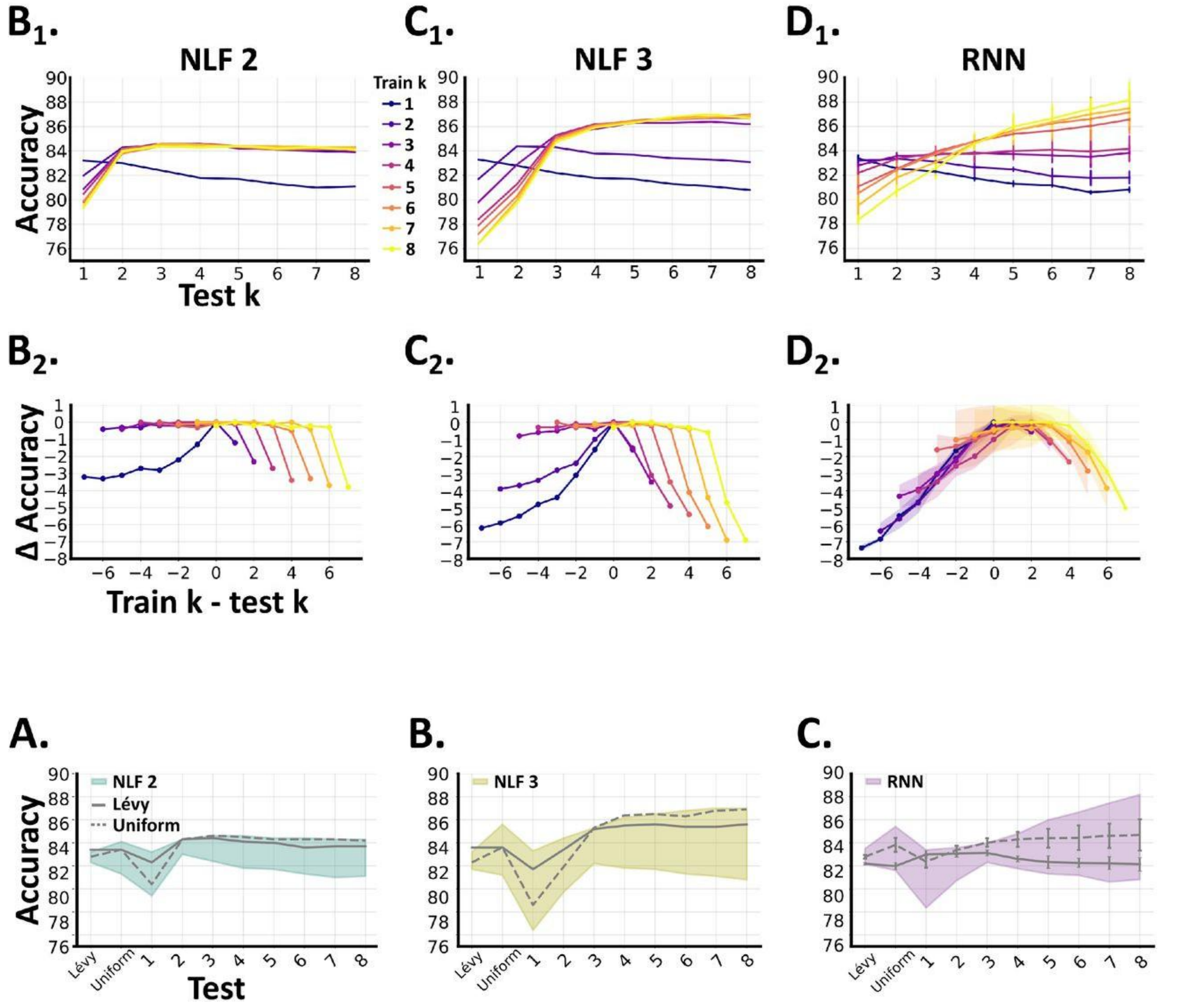


10,903 params

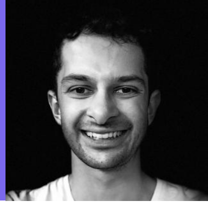
Result: simpler models seem to work better

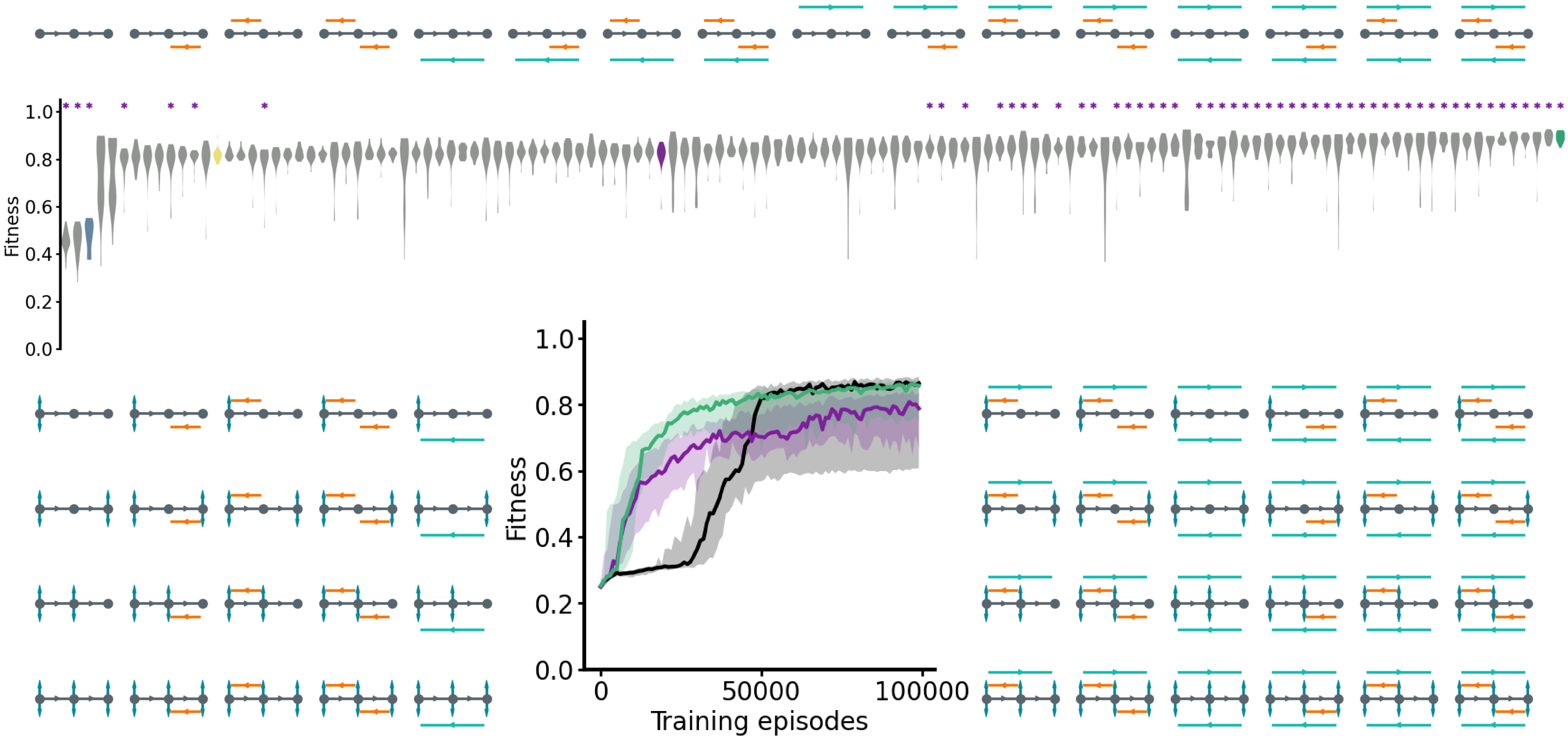


k = length of signal bursts



Preview: more complex set of tasks, more architectures





Conclusion / discussion

Did we answer the question of what neural architectures are good for?

No. Of course not. Sorry for suggesting that I would answer this in my social media posts.

But, we have some cool theory-based methods that can start to answer these.

We saw that:

- Structural and functional modularity are not necessarily linked.
- Although maybe they are when resources are tight.
- In a multimodal setting, as task complexity increases, the importance of architecture and nonlinear neurons increases.
- Just jumping straight to a full recurrent neural network may not be ideal, either for performance or understanding.

Big take home for me is this:

We need to study more complex tasks but in a controlled way. Challenging!

Thanks!

Gabriel Béna
PhD student 2021-

Béna and Goodman (2025)
Nature Comms

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And **thank you** for listening!