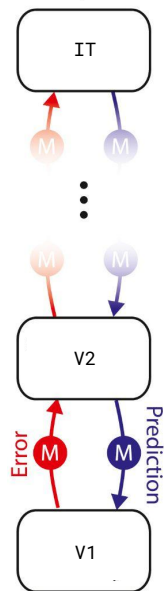


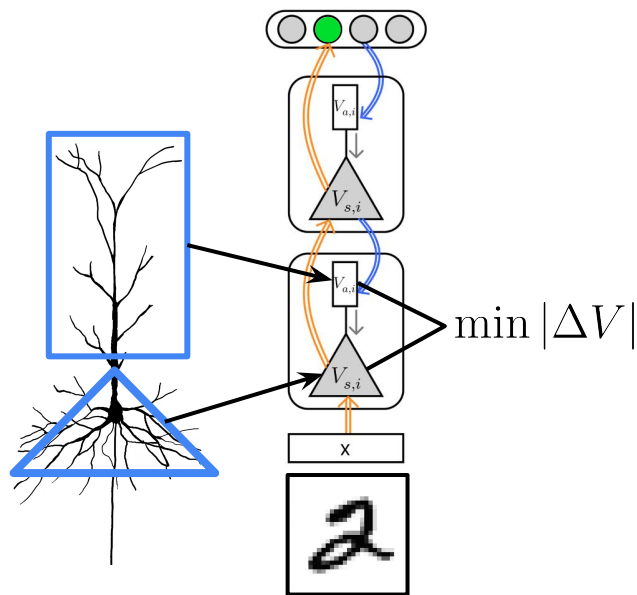
Predictive Coding in SNNs using Energy Optimization

Predictive Coding 101

PC hypothesis: brain forms prediction errors about the world

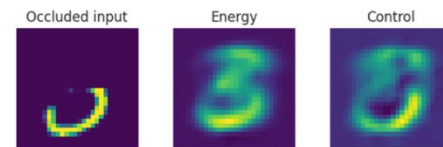


Investigating PC using energy-minimizing SNNs with compartmental neuron models

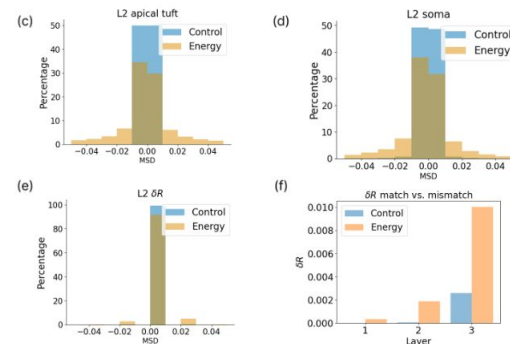


Energy-minimizing SNNs exhibits key characteristics of PC

Recon. from internal repr.

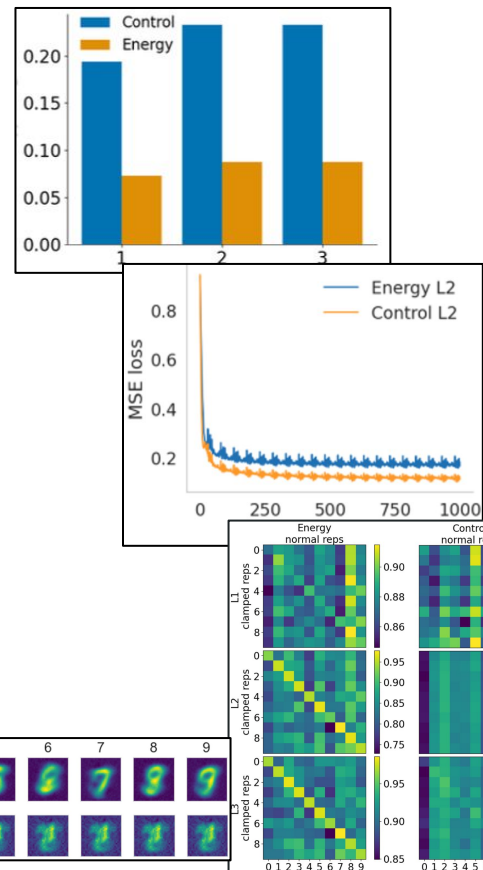


Mismatch behavior



Motivation: energy optimisation in the brain

- **Neuroscience:** energy consumption of brain is 20-25 Watt [1]
 - **Main energy consumption:** propagation of action potentials (i.e. spikes)
- Our SNN energy model [2] uses a local, indirect energy term:
 - Reduces spike rate
 - Decreases classification performance
 - Enables PC characteristics
- What happens when we directly **penalize spiking**?
 1. How does the *control+spike* model perform at equal spike rate?
 2. Does the *control+spike* model show PC characteristics?
 3. How does the *energy+spike* model perform?



[1] Balasubramanian V. Brain power. 2021.

[2] Zhang M, Chitic R, Bohte SM. Energy Optimization Induces Predictive-coding Properties in a Multicompartment Spiking Neural Network Model. 2024.

Methods: introduce spike loss term

$$\mathcal{L}_t = \mathcal{L}_{clf,t} + \alpha_{reg} \mathcal{L}_{reg} + \alpha_{spike} \mathcal{L}_{spike} + \alpha_E \mathcal{L}_E$$

- Four classes of models:

- Control
- Control+Spike
- Control+Energy
- Control+Energy+Spike

- Parameters:

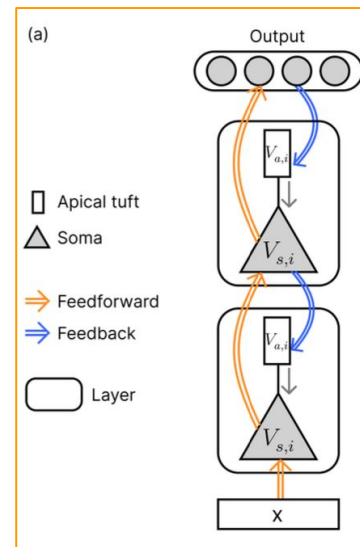
- α_E
- α_{spike}

$$\mathcal{L}_{spike} = \frac{\sum_{L=1}^3 n_L}{BD}$$

- n_L : number of spikes per layer L
- B: batch size
- D: total dimensions of network

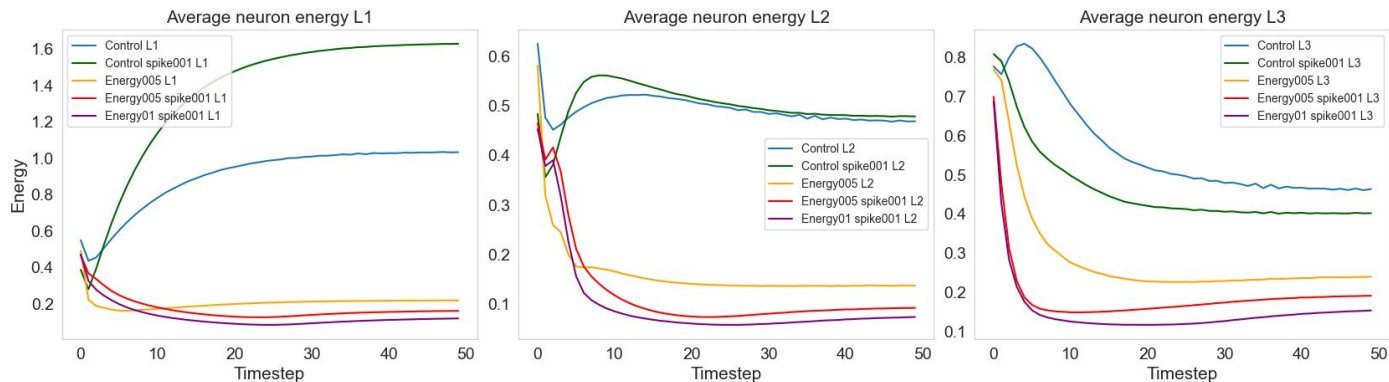
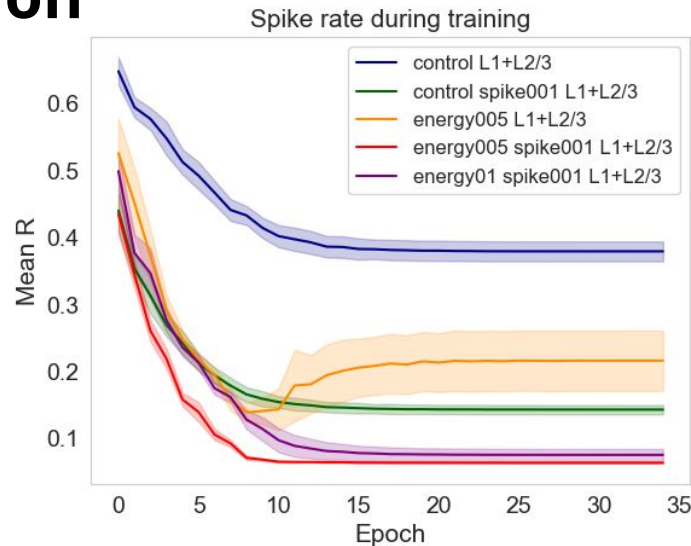
$$g(V_{a,i}^l(t), V_{s,i}^l(t)) = |V_{a,i}^l(t) - V_{s,i}^l(t)|,$$

$$\mathcal{L}_{E,t} = \left(\sum_l \sum_i g(V_{a,i}^l(t), V_{s,i}^l(t)) \right) / N,$$



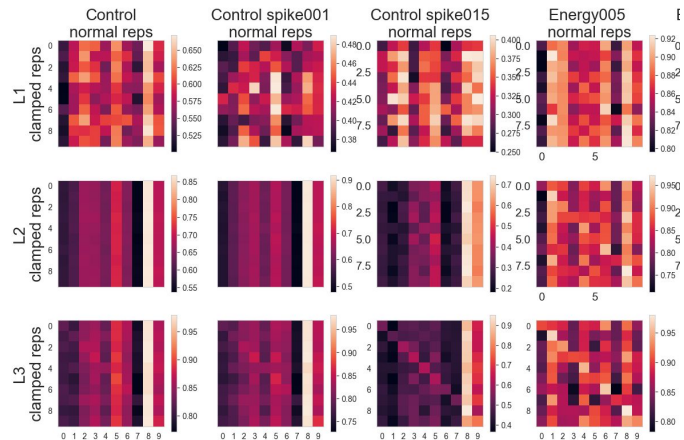
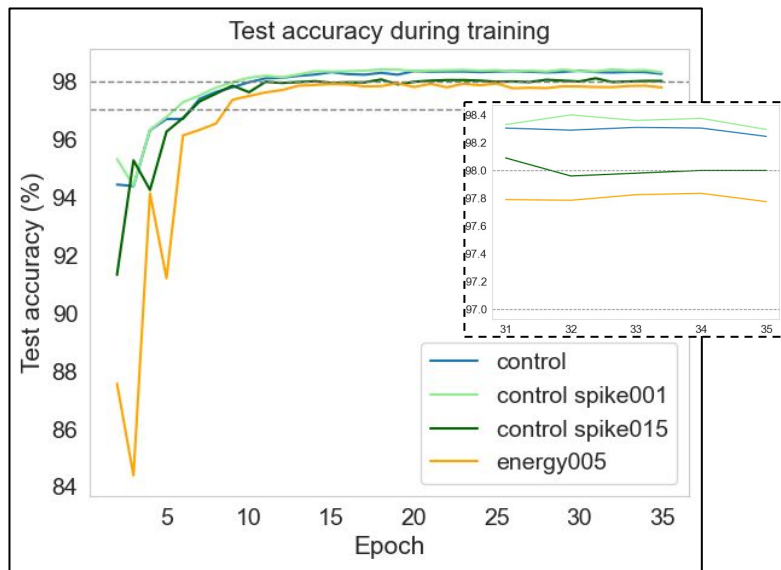
Results: spike rate & energy per neuron

- Spike rate differs per epoch
- *Spike* models reduce spikes rates
- *Control+spike001* gives approx. equal spike rate to *energy005*
- *Energy* models have much reduced average neuron energy compared to *control* models
- *Spike* models slightly reduce average neuron energy



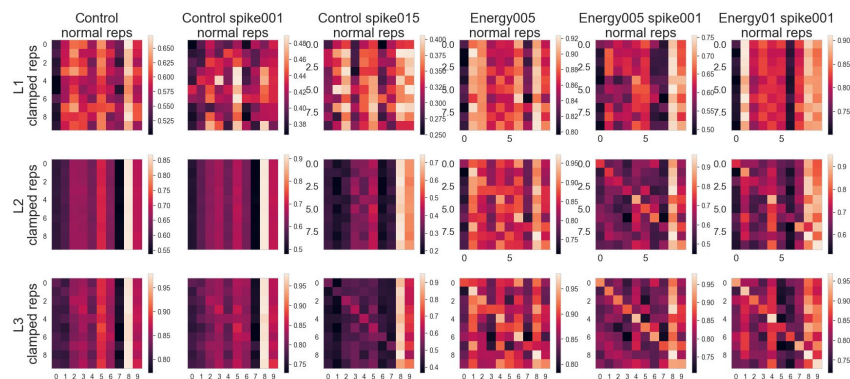
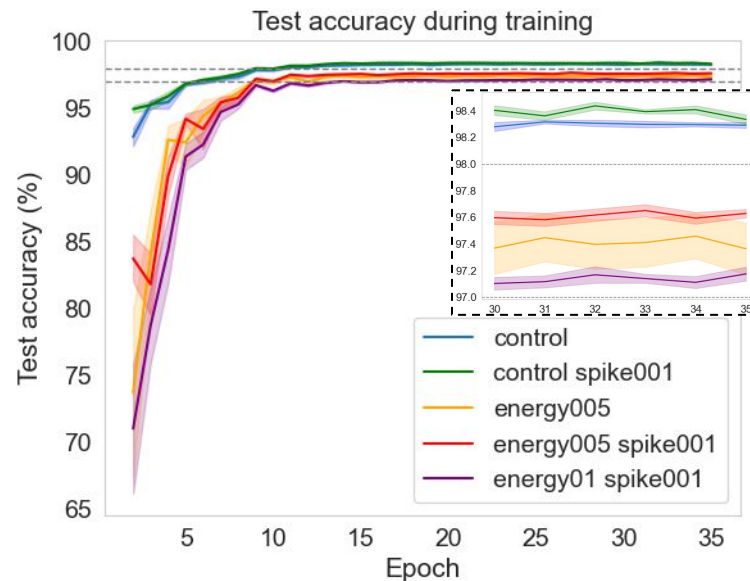
Results: *control+spike*

- Classification accuracy:
 - Moderate-high α_{spike} : *spike* models **reduce** test accuracy of *control+spike* models
 - Low α_{spike} (<0.03): *spike* models can slightly **improve** test accuracy of *control+spike* models (regulator characteristics)
- Generative features
 - Moderate-high α_{spike} : slight generative features but much worse than *energy* models
 - Low α_{spike} (<0.03): no noticeable generative features



Results: *energy+spike001*

- Classification accuracy:
 - Moderate-high α_E (0.10): **reduced** test accuracy of *energy+spike* models
 - Low α_E (0.05): *spike* models can slightly **improve** test accuracy of *energy+spike* models (regulator characteristics)
- Generative features
 - Moderate-high α_E : slight generative features but much worse than *energy* models
 - Low α_E : slightly **improved** generative features



Conclusions - control+spike & energy+spike

- *Spike* models significantly **decrease** spike rate of both *control* and *energy* models
- Low α_{spike} (<0.03),
 - slightly **increases** classification performances of both *control* and *energy* models
 - slightly **increases** generative features for *energy* models while no noticeable effect for *control* models
- Moderate-high α_{spike} ,
 - **decreases** classification performances of both *control* and *energy* models
 - slightly **decreases** generative features for *energy* models while slightly **increasing** generative features for *control* models
- Increasing α_E **decreases** performance for *energy+spike001* models

Conclusions - research questions

- What happens when we directly **penalize spiking**?
 1. How does the *control+spike* model perform at equal spike rate?
 2. Does the *control+spike* model show PC characteristics?
 3. How does the *energy+spike* model perform?

1. *Control+spike001* has most comparable spike rate to *energy005* & performs best of all models in classification. Significantly better than *energy005*.
2. *Control+spike001* shows no PC characteristics, interestingly *Control+spike015* does slightly better
3. *Energy005+spike001* performs somewhat better than *energy005* in both classification & generative performance while decreasing spike rate. However, *energy01+spike001* decreases performance in comparison to *energy005*.

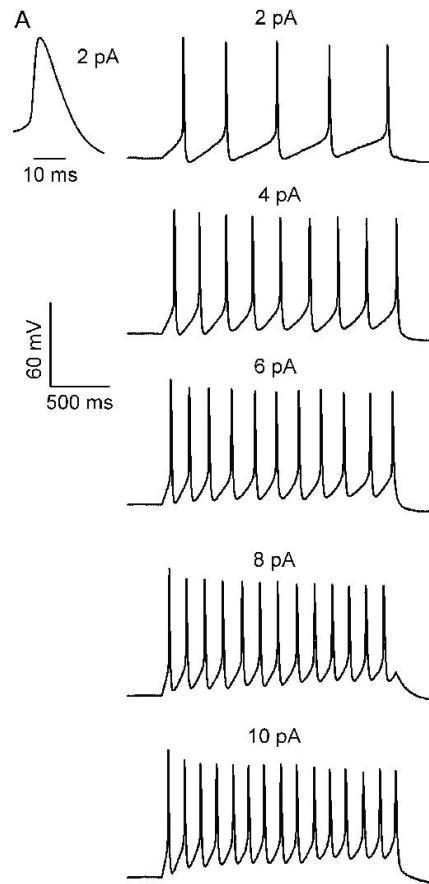
Discussion & future research

- **Remaining questions**

- Does the diagonal of pair-wise representation actually correlate to generative features?
 - If yes, does the *control+spike015* model give indication for PC features?
- Does the *control+spike015* show other PC characteristics?
- What happens to *energy+spike* models with moderate-high α_{spike} ?

- **Future research**

- Small spike loss term seems to improve performances of *control* & *energy* models. Check whether this holds for other SNN models
- Explore different ways of implementing spike loss term
- Find more suitable metrics for generative/PC features



Questions?