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An anatomically accurate circuit for short- and long-term motivational learning in fruit flies

Evripidis Gkanias[1], Li Yan McCurdy[2], Michael N Nitabach[2] and Barbara Webb[1]

[1]School of Informatics, University of Edinburgh

[2]Department of Cellular and Molecular Physiology, Yale School of Medicine

THE UNIVERSITY of EDINBURGH informatics

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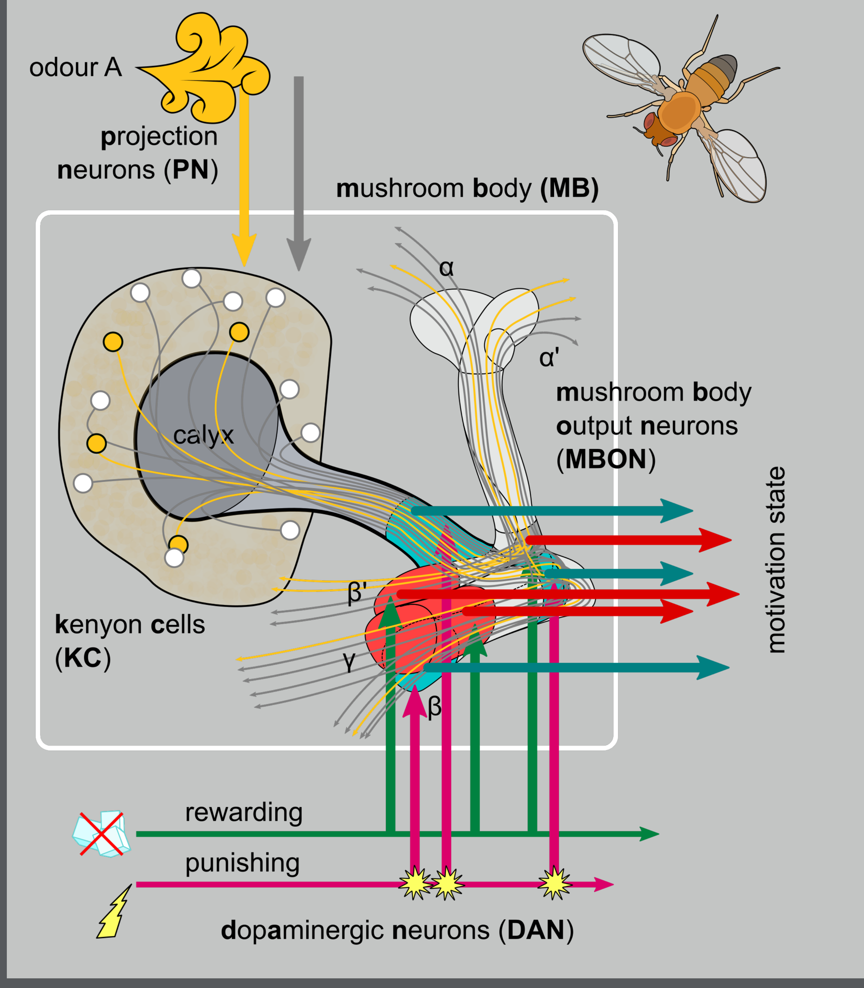
Abstract

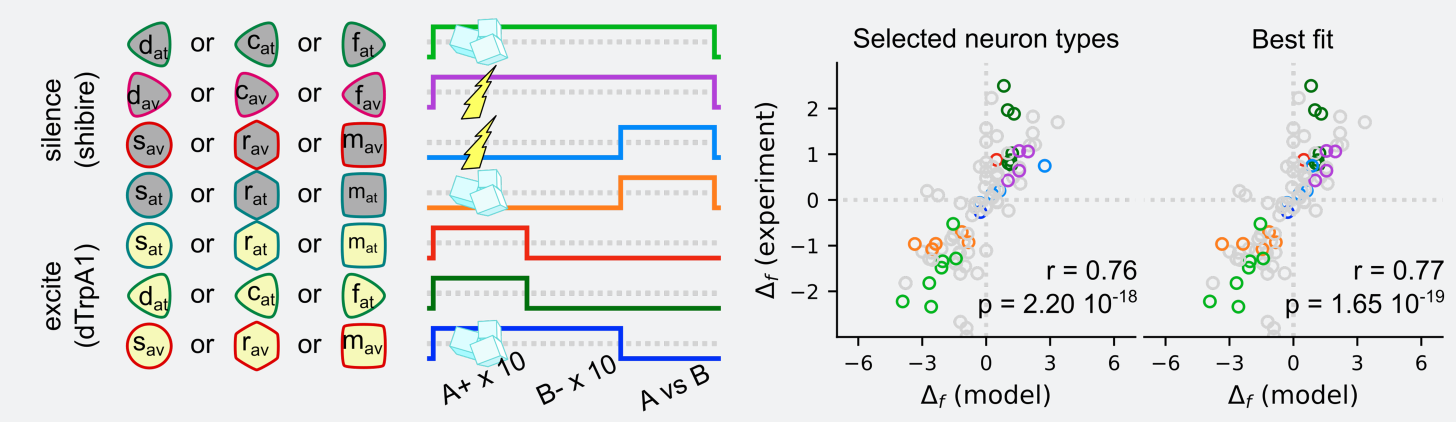
1. Key circuits for associative and reinforcement learning have been identified in the mushroom body neuropils of the insect brain [1, 2].
2. Detailed imaging, electrophysiological and structural data about the mushroom bodies in *Drosophila melanogaster* has led to the identification of a variety of microcircuits involved in memory.
3. In [3], we propose a comprehensive scheme, based on the connectivity and the responses of identified neurons in the mushroom bodies.
   - We link these known microcircuits together as an incentive circuit that acquires, forgets and assimilates associative memories over different timescales.
   - We suggest that our novel dopaminergic plasticity rule increases the adaptation capabilities of the overall circuit.

About the mushroom bodies



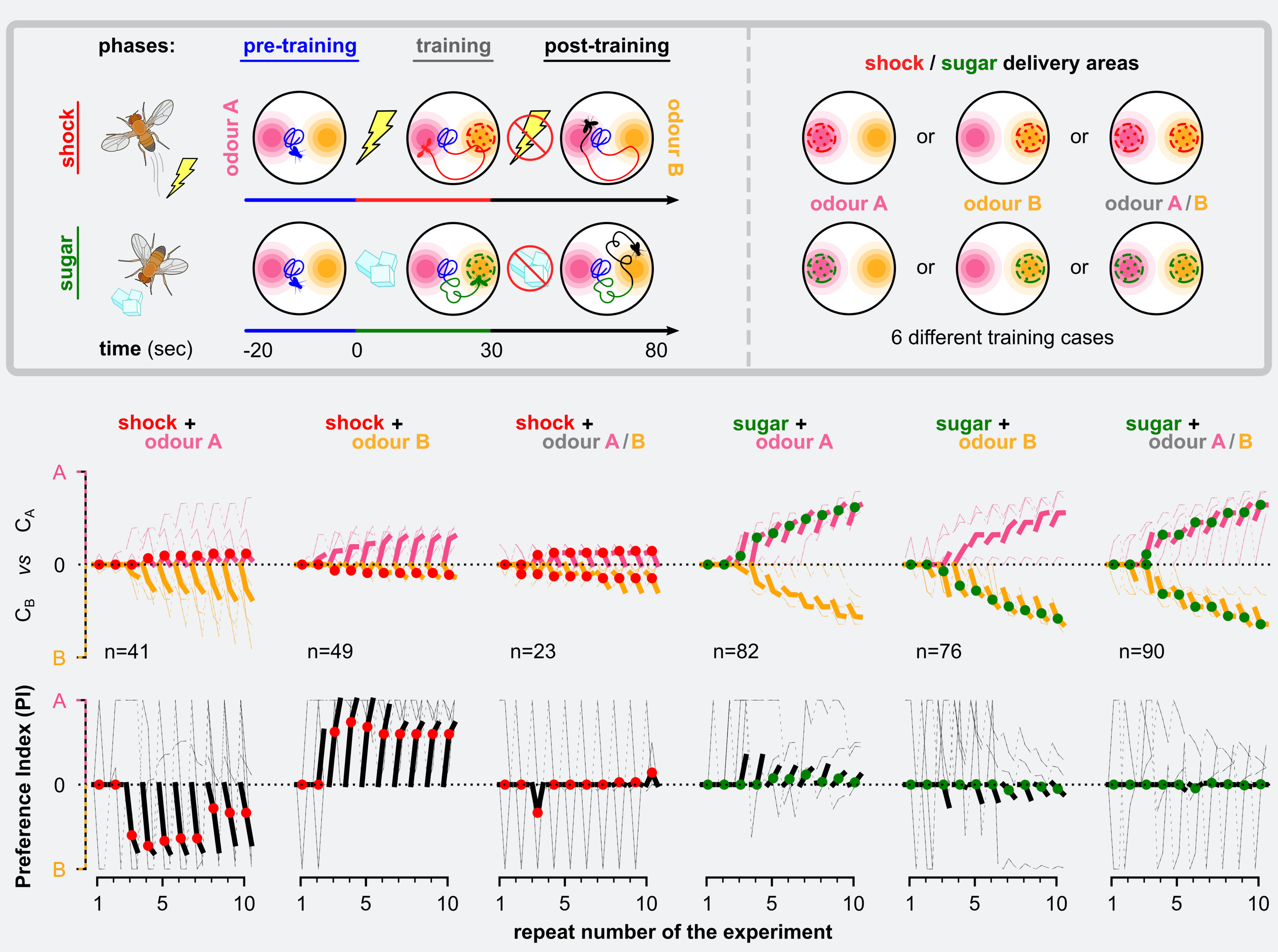
- Sensory input is projected onto the calyxes, from where the numerous kenyon cells (KCs) distribute it to the much fewer output neurons (MBONs).
- Dopaminergic neurons (DANs) deliver multi-dimensional reinforcement signals and modulate the KC-to-MBON synaptic weights.

Results: classical olfactory conditioning



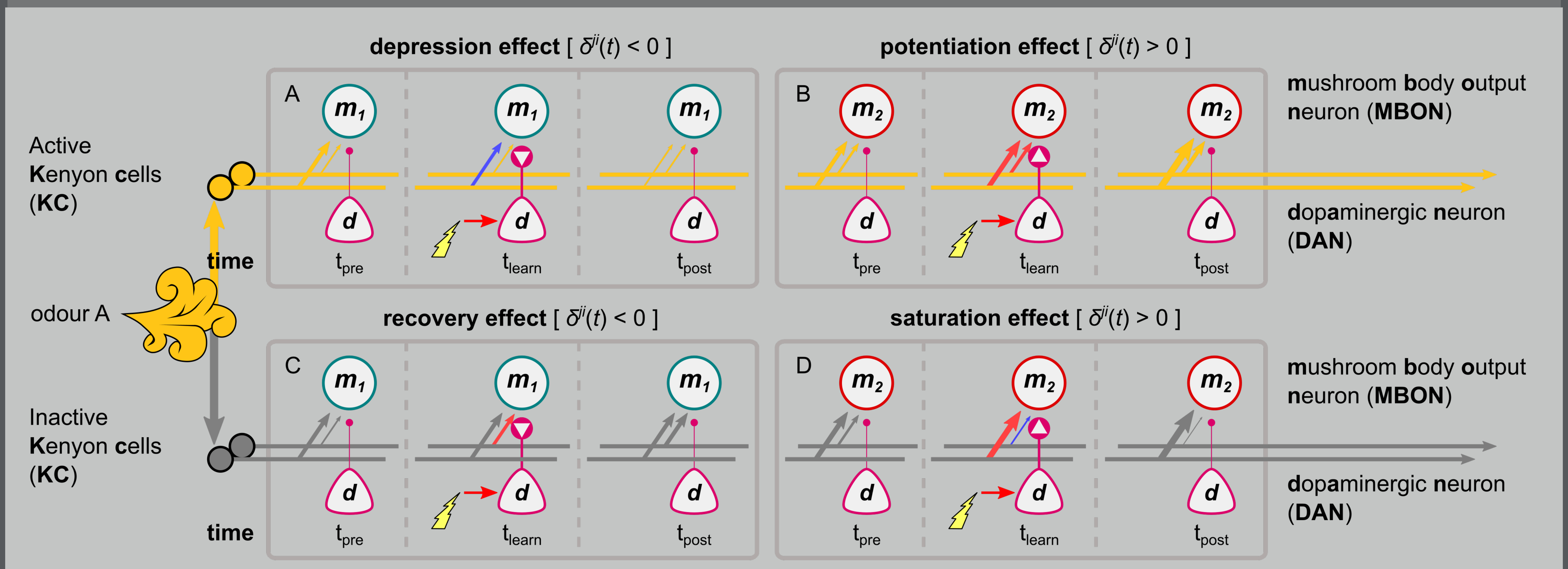
- Our predictions correlate with 92 intervention experiments from 14 studies (data and method from [4]).

Results: modelling the behaviour



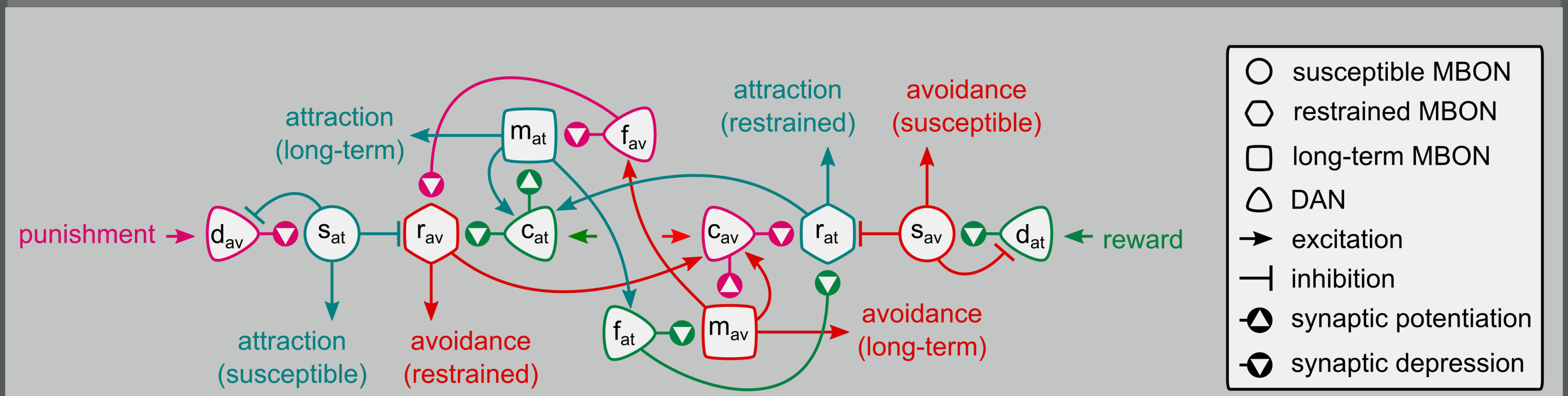
- We further verify the function of the incentive circuit by demonstrating how the reproduced responses of the output neurons could drive the behaviour of a virtual fruit fly, creating similar odour preferences to the real flies.

Model: the dopaminergic plasticity rule



- Update of the KC-to-MBON synaptic weights:
$$\Delta W^{ij}_{k2m}(t) = \delta^{ij}(t)[k^i(t) + W^{ij}_{k2m}(t) - w_{\text{rest}}]$$
- $\delta^{ij}(t) = D^{ij}_{\triangle}(t) - D^{ij}_{\triangledown}(t)$ controls the learning at the KC^i-to-MBON^j synapse.
- $k^i(t)$ is the KC activity.
- $w_{\text{rest}} = 1$ is the resting value.
- $D^{ij}_{\triangle}(t)$ and $D^{ij}_{\triangledown}(t)$ are components of the dopaminergic signal, with a short and a long time-constant respectively, that are key for explaining backward learning [5].
- Depending on conditions, this synaptic modulation causes weights to stabilise or to increase with positive feedback
  - We exploit these properties to enable short- and long-term memories, respectively, to be formed and forgotten in parallel for different contexts.

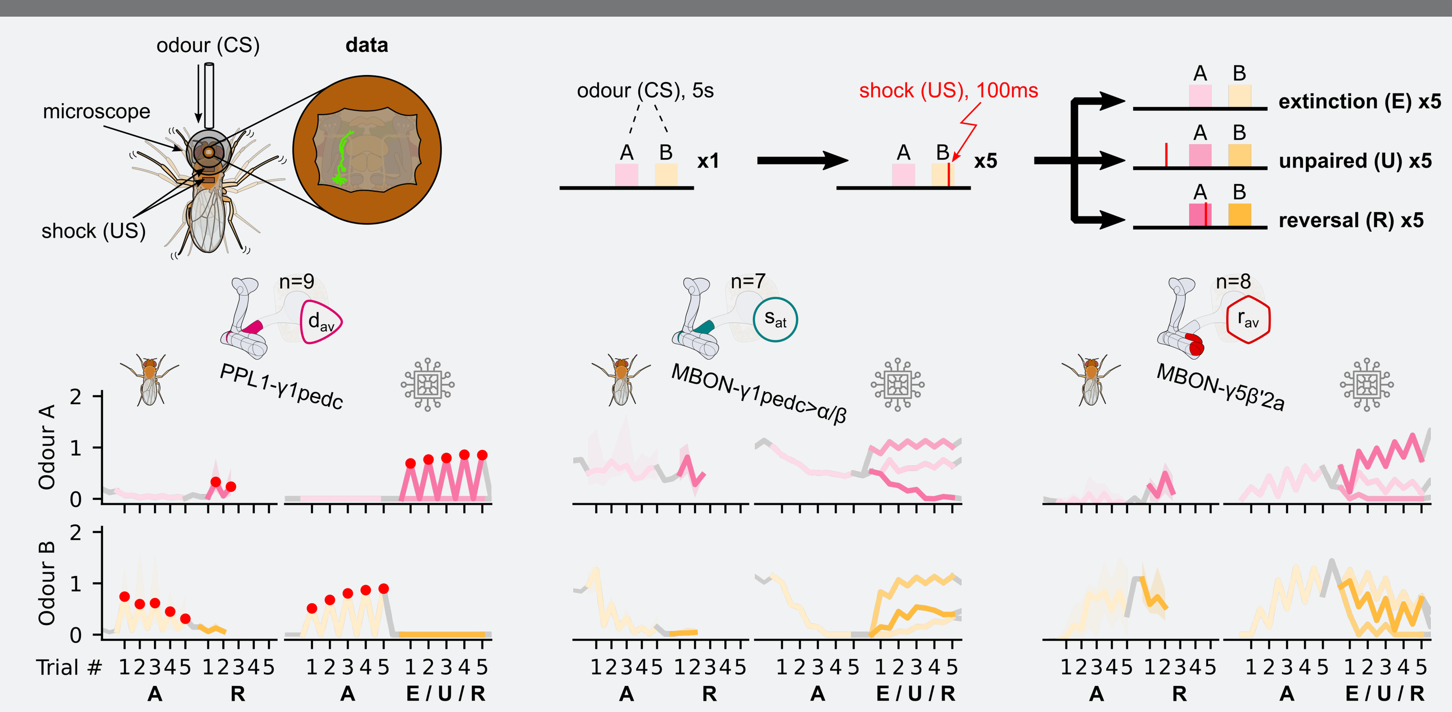
Model: the incentive circuit



- Susceptible (s) MBONs underlie primitive memories.
- Restrained (r) MBONs underlie flexible memories.
- Long-term memory (m) MBONs.
- Anatomically validated: each connection exists in the fly brain.
- Discharging (d) DANs.
- Charging (c) DANs.
- Forgetting (f) DANs.
- Note: KCs are not shown.

Results: modelling the neural responses

- We can replicate experimental observations of the response dynamics of specific neurons during odour-shock association in
  - acquisition and
  - variable forgetting stages.



Conclusion

- The dopaminergic plasticity rule is an alternative to prediction error plasticity rules, and within the incentive circuit can support acquisition, forgetting and assimilation of memories.
- Different MBONs hold primitive, flexible or long-term memories, supporting flexible exploration/exploitation trade-off in an olfactory conditioning task.

EPSRC Engineering and Physical Sciences Research Council

References

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