Arousal-induced changes in functional brain networks during exploration and exploitation

Nathan Tardiff, Danielle S. Bassett, & Sharon L. Thompson-Schill

Penn UNIVERSITY of PENNSYLVANIA

CENTER FOR COGNITIVE NEUROSCIENCE

BACKGROUND

- What mechanisms allow the brain to rapidly shift between different cognitive processes and maintain a balance between the stability necessary to support ongoing behavior and the flexibility necessary to adapt to new exigencies?
- Cognitive performance appears to be supported by large-scale, dynamic changes in functional brain connectivity [1,2].
- Neuromodulatory actions of norepinephrine (NE) may help facilitate these changes [3,4].
- Here we probed the relationship between NE and network dynamics within an exploration/exploitation task, a type of task that is known to induce changes in NE activity as measured by pupil diameter [5].

HYPOTHESES

Both more *integrated* brain network states and moderate NE activity facilitate focused task performance (*exploitation*), while less integrated states and high NE activity lead to distraction/error (*exploration*) [2, 6]. Therefore we expect:

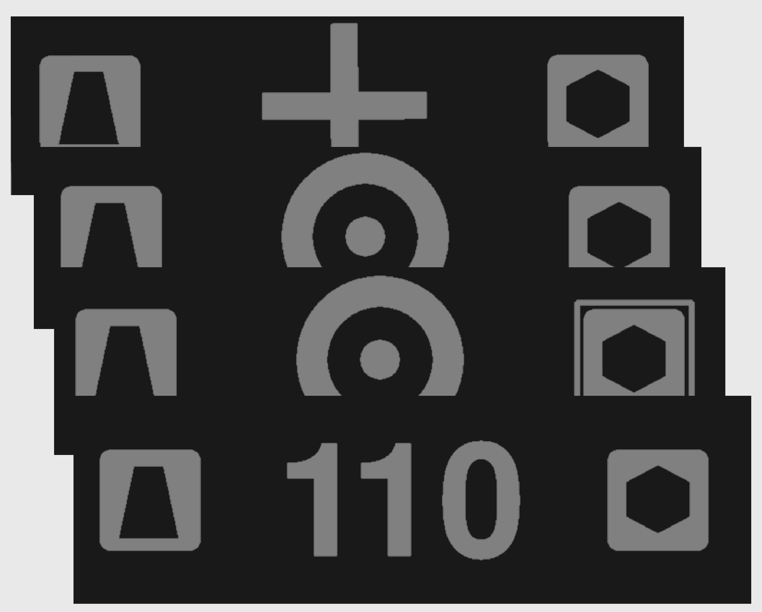
- **Across blocks, average baseline pupil diameter will be associated with less integration between modules.**
- **Within blocks, network integration will be correlated with behavior (exploitative vs. exploratory) and pupil diameter.**

METHODS

Subjects

N=9 completed 4 fMRI runs (80 trials/run) of an isoluminant version of the Leapfrog bandit task [7] while undergoing continuous pupillometry

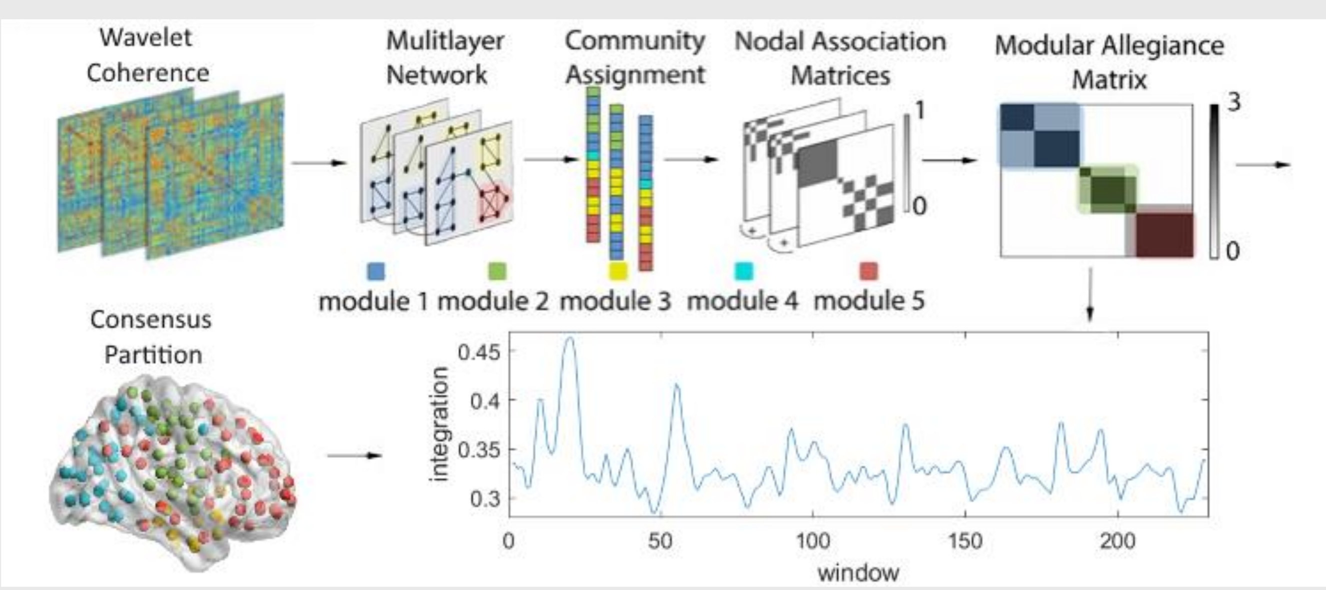
Leapfrog Bandit



A simplified bandit task

- Two armed
- Deterministic reward
- Fixed distance between options
- Options "take turns" being the best, changing based on underlying P_{flip}
- **Goal:** Always choose the option that is currently the best. This requires balancing ***exploration*** and ***exploitation***.
- Two Block types: Low volatility (P_{flip} = 0.05), High volatility (P_{flip} = 0.20)
- Volatility level alternates between runs, order counterbalanced across subject

Network Construction

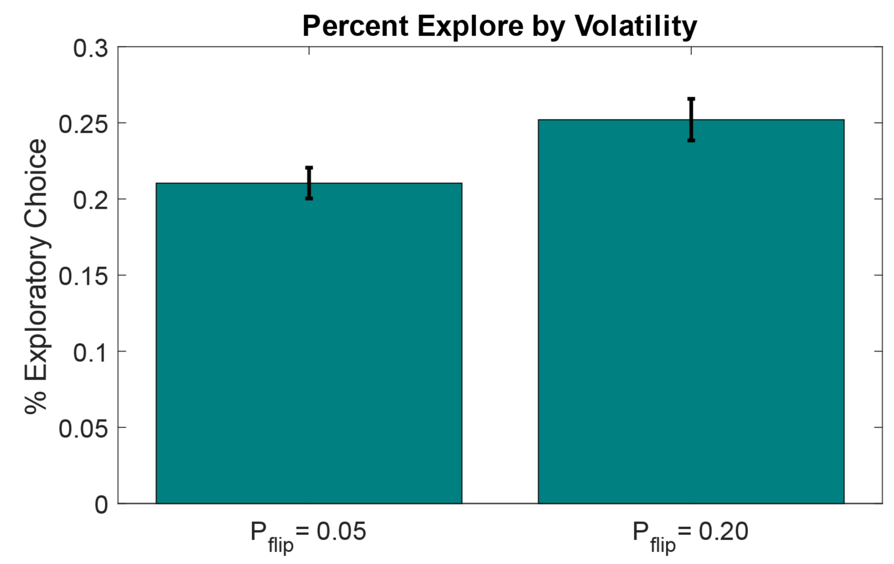


RESULTS

Task Performance

Exploratory choice

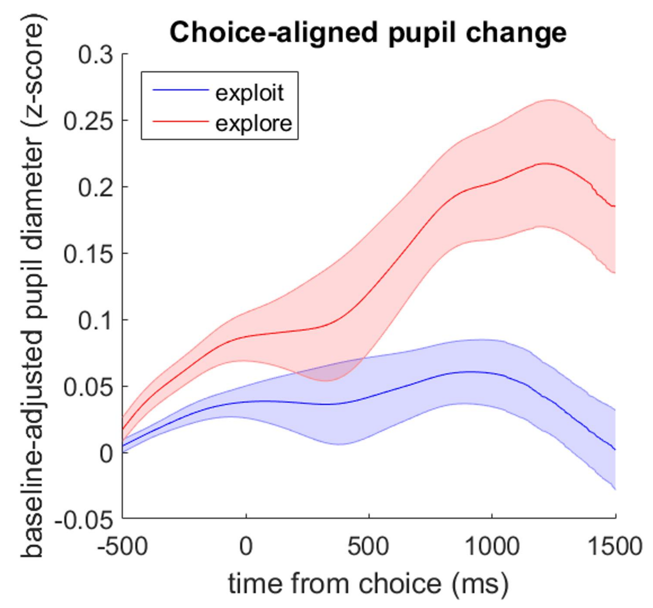
- Subjects are sensitive to volatility condition, demonstrating increased exploration in high volatility vs. low volatility blocks ($t(8) = 3.11$, $p = .01$)
- However the exploration difference is less than might be expected given the volatility difference (mean # of flips: $M_{low} = 3.72$ (1.18), $M_{high} = 14.67$ (2.87), $t(8) = 10.71$, $p < .001$).

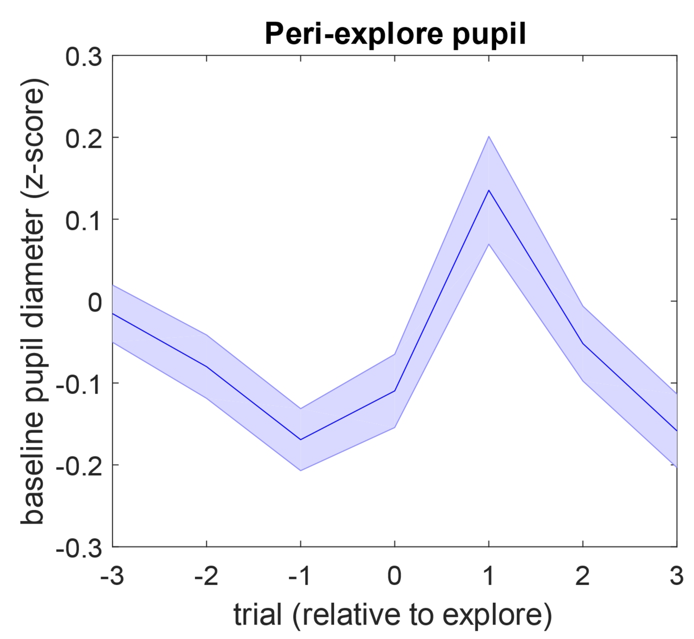


Pupil-linked Arousal

Explore vs. Exploit Trials

- Post-choice pupil dilation (max deviation from pre-trial baseline) is reliably larger on explore trials than exploit trials ($M_{explore}$ = 0.45 (0.16), $M_{exploit}$ = 0.32 (0.09), $t(8) = 4.27$, $p = .003$).



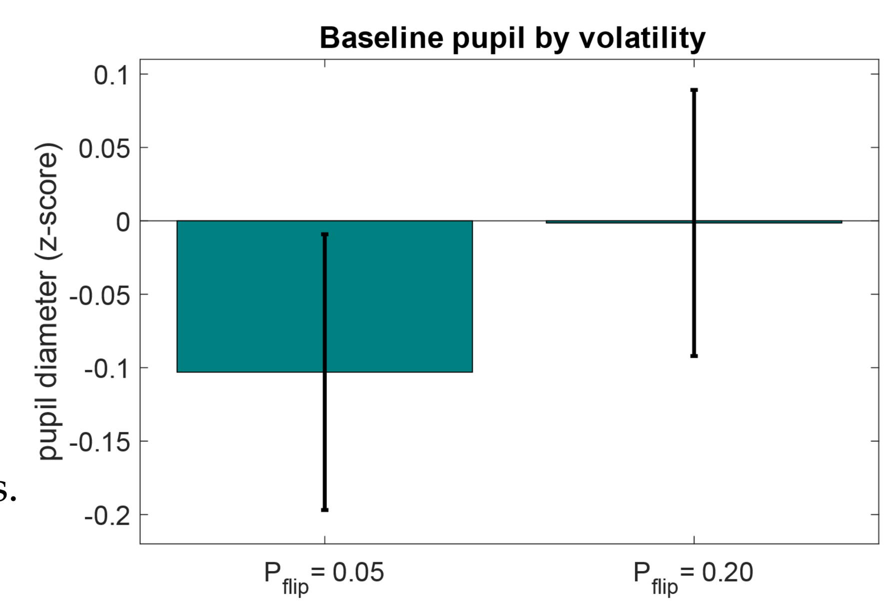


Peri-explore Pupil

- Baseline pupil diameter (reflecting tonic NE activity) falls in the 3 trials preceding exploration ($F(1,8) = 21.48$, $p = .002$), rises over the 3 trials centered on exploration ($F(1,8) = 16.66$, $p = .004$), and falls over the 3 trials following exploration ($F(1,8) = 12.37$, $p = .008$).
- This pattern is confirmed by an overall cubic trend ($F(1,8) = 16.72$, $p = .003$).

Block-level arousal

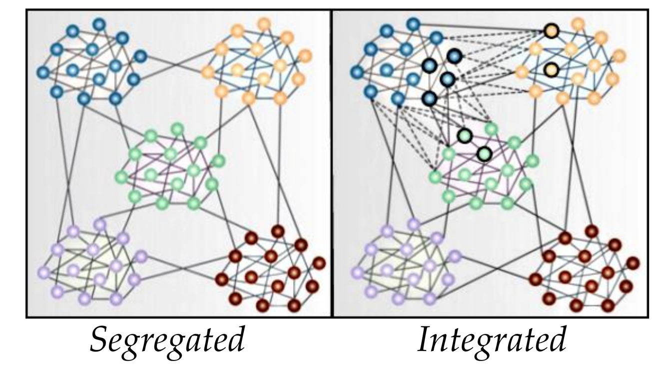
- High volatility blocks have higher average baseline pupil diameter than low volatility blocks, but this difference failed to reach significance ($t(8) = 0.56$, $p = .59$).
- Our block-level arousal manipulation does not yet show success, possibly due to the very small difference in exploratory choice between conditions.



Pupil-linked Arousal and Integration

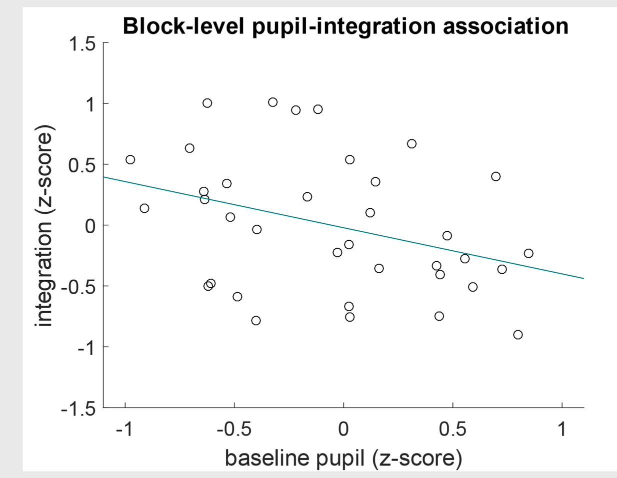
Integration

- Measures the degree to which nodes in separate modules functionally interact.
- It is calculated from the fraction of time windows during which regions generally belonging to two different communities are assigned to the same community.

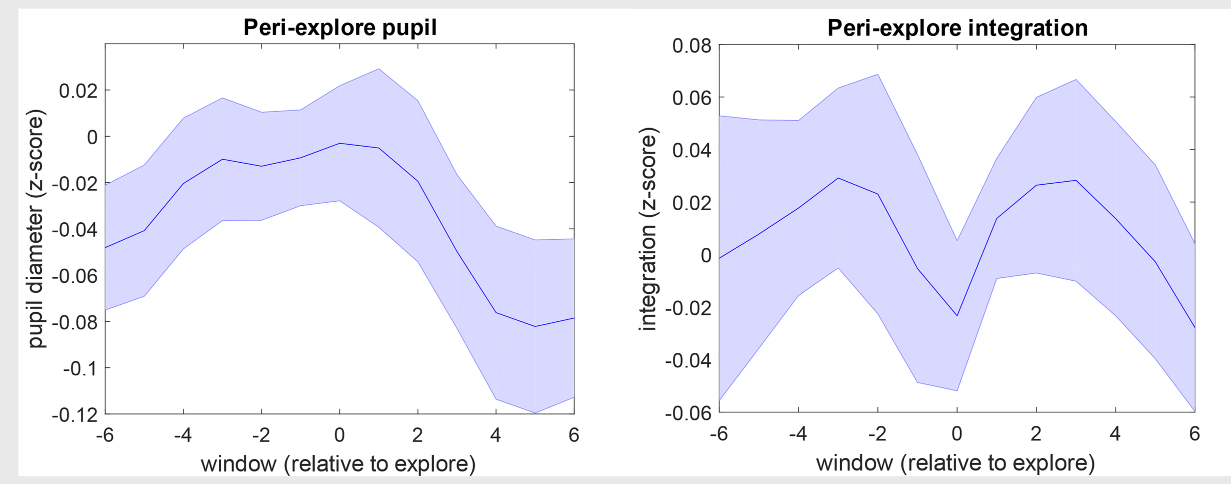


Block level

- Across all data, average baseline pupil diameter is negatively related to block-wise brain network integration ($r = -.36$).
- This relationship is reliable across subjects ($t(8) = -3.82$, $p = .005$).



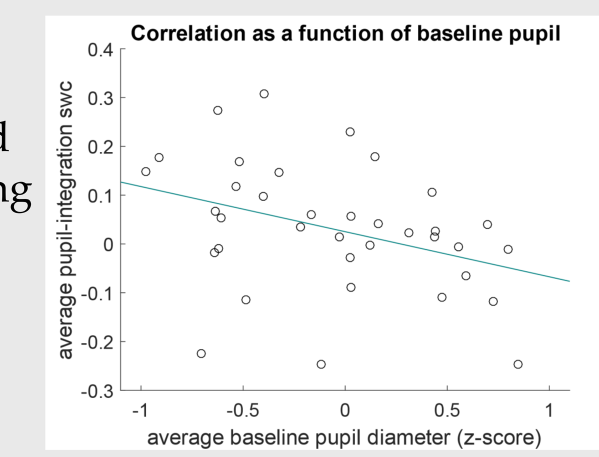
Peri-explore (24s sliding window)



- **Identifiability of exploration-induced changes:** The quadratic trend for peri-explore pupil is reliable at a $.05 < p < .10$ level ($F(1,8) = 3.75$, $p = .089$). The apparent dip in integration around exploration is not significant.

Nonlinear effects?

- Pupil-integration correlations were computed in 20 window sliding windows, demonstrating large variance across all data [M = .03 (0.48)].
- Block-wise average correlations are related to average baseline pupil diameter ($r = -.37$).
- This relationship is reliable across subjects ($t(8) = -2.83$, $p = .02$).



SUMMARY & CONCLUSIONS

- We replicate the pupil responses to exploratory choice found in [5].
- We confirm our prediction of decreased integration with increasing baseline pupil diameter at the block level.
- Within block, there is a nonsignificant dip in integration during exploration. This effect may not be robust due to a potential nonlinear relationship between integration and pupil diameter that appears dependent on baseline pupil diameter. Our window size may also be too large.
- Overall, these results support a role for NE in brain network reconfiguration.

ACKNOWLEDGEMENTS

Funding for this research was provided by NIH grant #R01DC009209.

CONTACT

Thompson-Schill Lab >>
ntardiff@sas.upenn.edu

REFERENCES

1. Braun et al. (2015). *PNAS.*
2. Medaglia, Lynall, & Bassett (2015). *J. Cog. Neurosci.*
3. Eldar, Cohen, & Niv (2013). *Nat. Neurosci.*
4. Shine et al. (2016). *Neuron.*
5. Jepma & Nieuwenhuis (2011). *J. Cog. Neurosci.*
6. Aston-Jones & Cohen (2005). *Annu. Rev. Neurosci.*
7. Knox et al. (2012). *Front. Psychol.*