Information integration and endogenous control during exploration and exploitation

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BACKGROUND

- Brain regions supporting adaptive behavioral adjustments should have access to information about current environmental and internal conditions and should have activity that varies with changes in cognitive state [1].
- Changes in arousal, including neuromodulatory actions of norepinephrine (NE), appear to facilitate behavioral adjustment, and are signaled in candidate integrative regions such as cingulate cortex [2,3].
- Changes in arousal may support changes in behavior via modulating large-scale brain networks [4,5].
- Here we took two complementary approaches to assessing information integration within the context of an exploration-exploitation task.

QUESTIONS

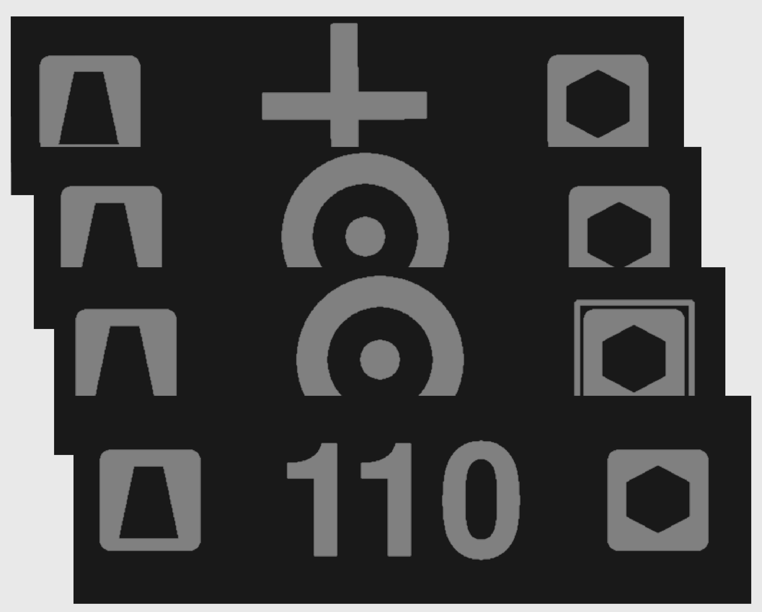
1. *Identifying integrative regions:* **Which brain regions are associated with the integration of arousal (pupil diameter), outcome (changes in value), and strategy (explore/exploit) information?**
2. *Consequences of behavioral adjustment:* **How does brain network integration change between exploration and exploitation?**
   Hypothesis: **Increases in arousal around exploration will lead to decreases in integration.**

METHODS

Subjects

N=19 completed 4 fMRI runs (80 trials/run) of an isoluminant version of the Leapfrog bandit task [6] while undergoing continuous pupillometry

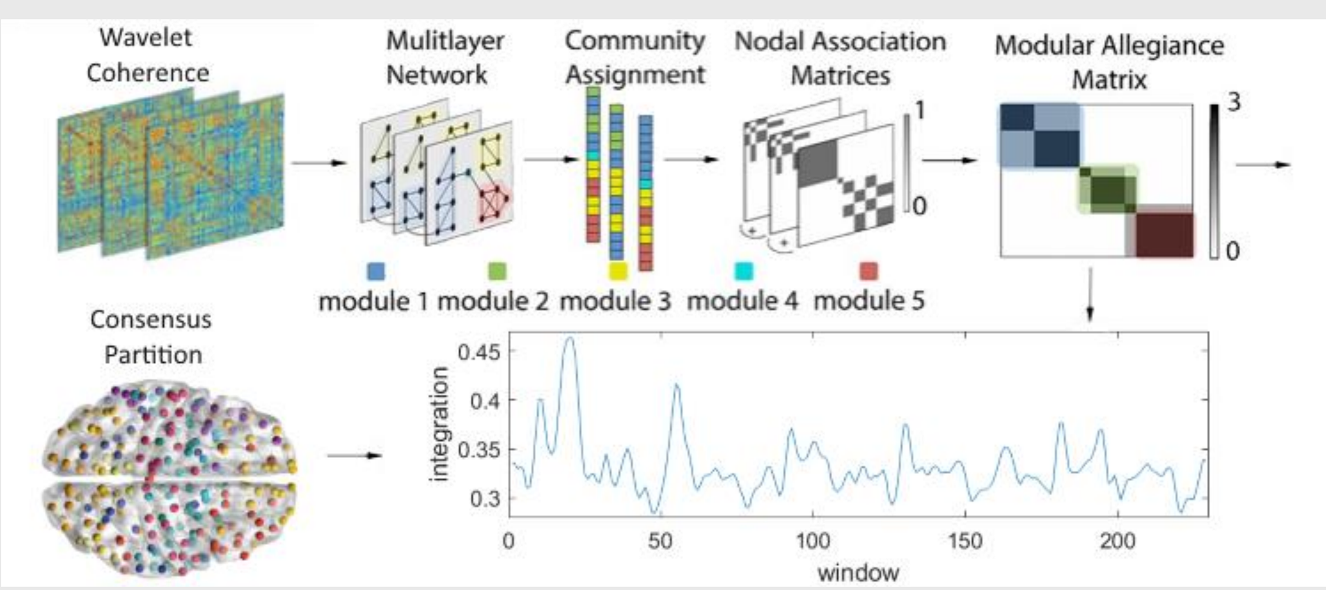
Leapfrog Bandit



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

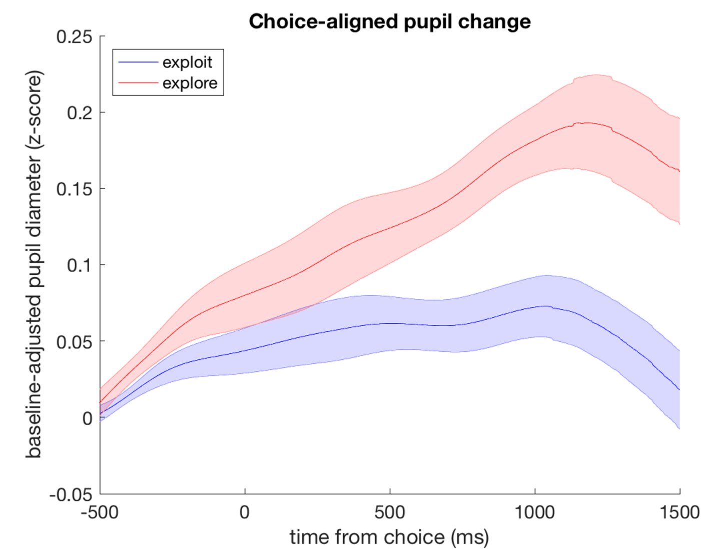


RESULTS

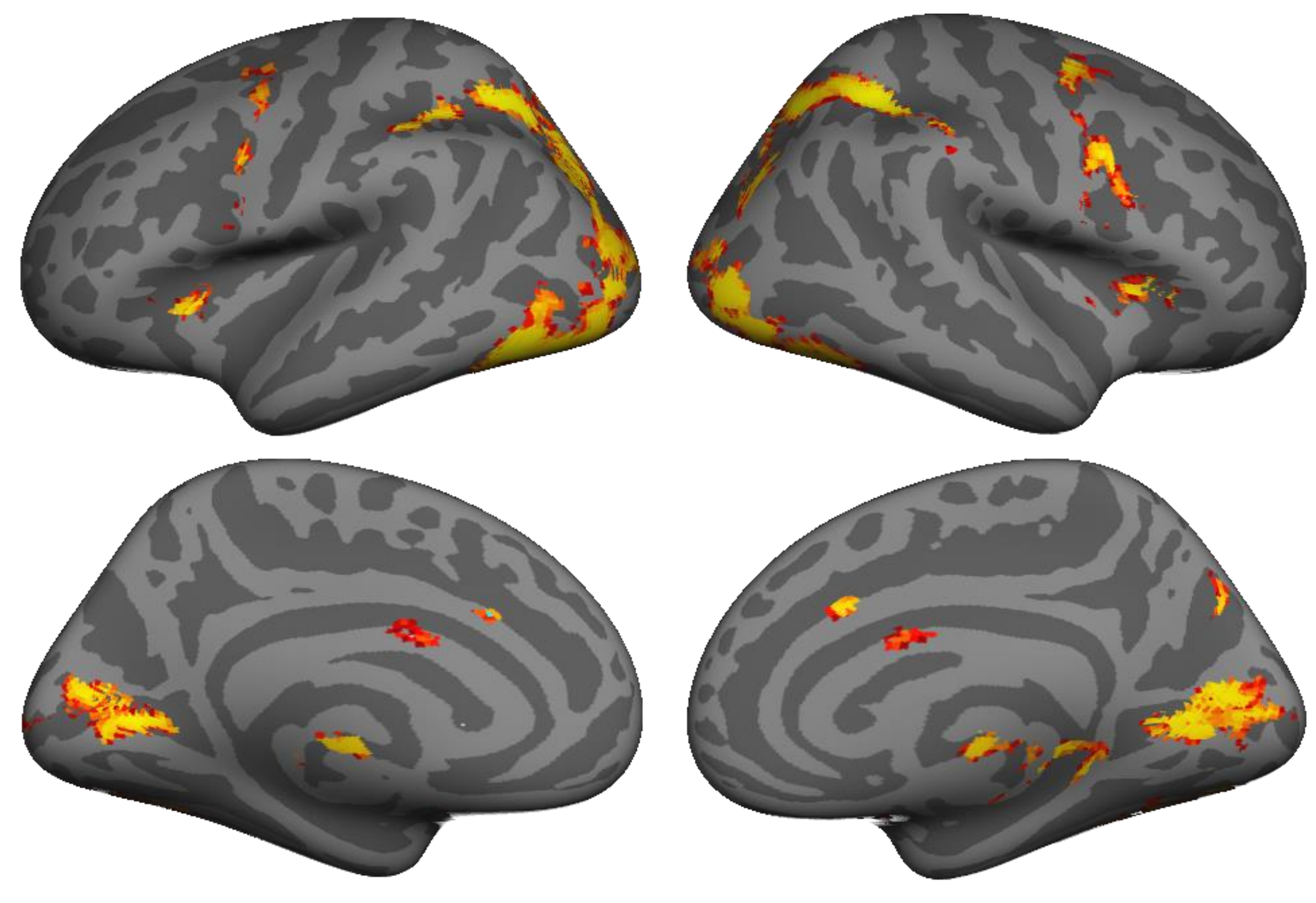
Pupil-linked Arousal

Exploration and Outcomes

- Post-choice pupil dilation (max deviation from pre-trial baseline) is reliably larger on explore trials [$M_{explore}$ = 0.45 (0.17)] than exploit trials [$M_{exploit}$ = 0.36 (0.14)], $t(18) = 3.53$, $p = .002$.
- Pupil dilation (max deviation from pre-outcome period) also increases when option values change [M_{change} = 0.39 (0.15), $M_{nochange}$ = 0.25 (0.08), $t(18) = 5.16$, $p < .001$].



Conjunction Analysis



- Conjunction of Explore > Exploit, Change > No Change, and Pupil < 0 reveals candidate regions for information integration and endogenous control.

SUMMARY & CONCLUSIONS

- We replicated the pupil responses to exploratory choice found in [7].
- We identified a set of regions previously associated with attention, cognitive control, and arousal as areas that could support integrative processing and behavioral adjustment.
- We confirmed that brain network integration decreases post-exploration.
- Decreases in integration, which largely involved frontoparietal regions, may be indicative of decreased top-down control during exploratory states.
- Jointly examining activation and network integration could help differentiate regions that implement changes in control state from those that are affected by such changes (e.g., visual cortex).

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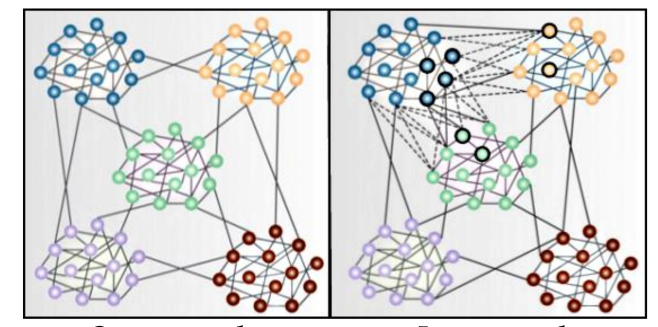
Network Integration

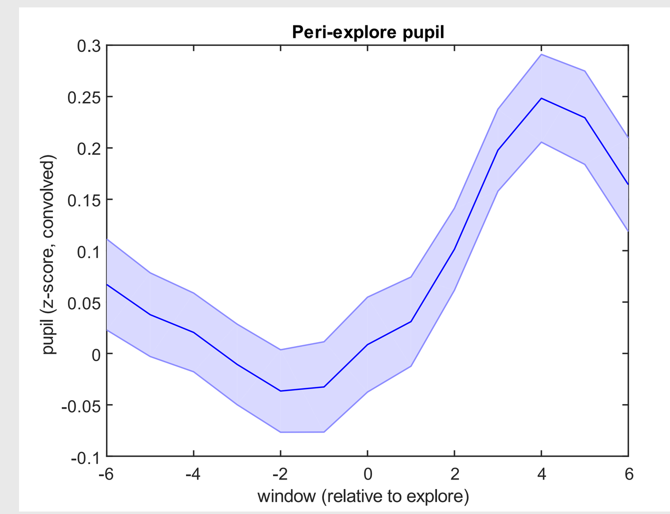
Integration

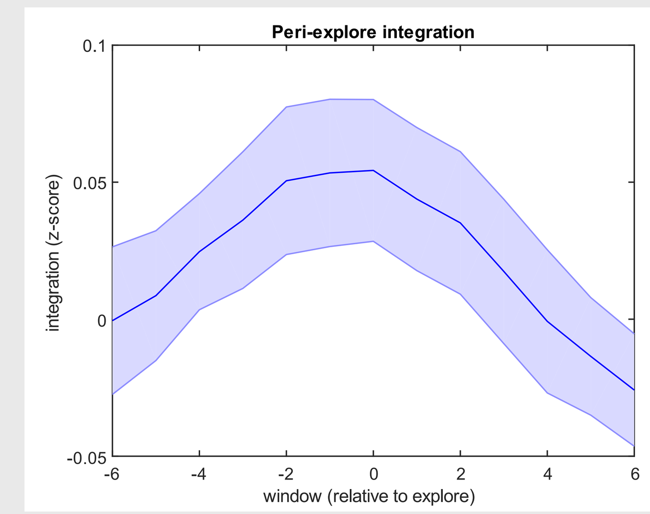
- Measures the degree to which nodes in separate modules functionally interact.
- It is calculated from the fraction of time windows during which regions generally belonging to two different communities are assigned to the same community.



Segregated *Integrated*

Peri-explore

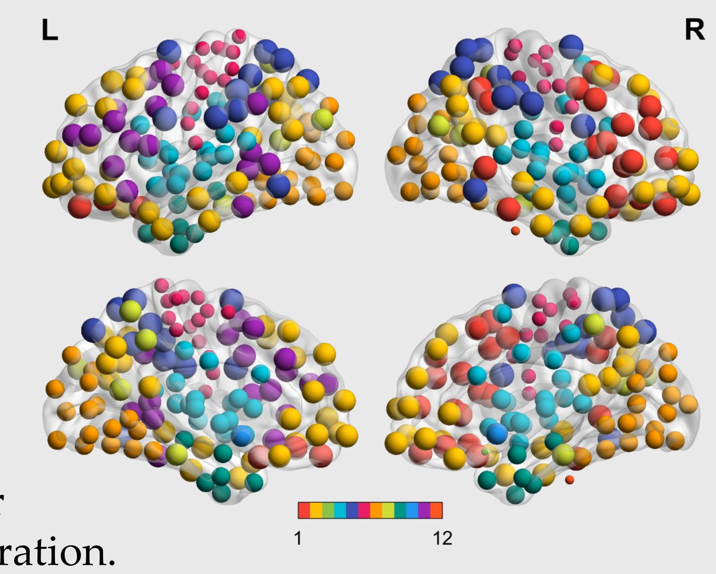


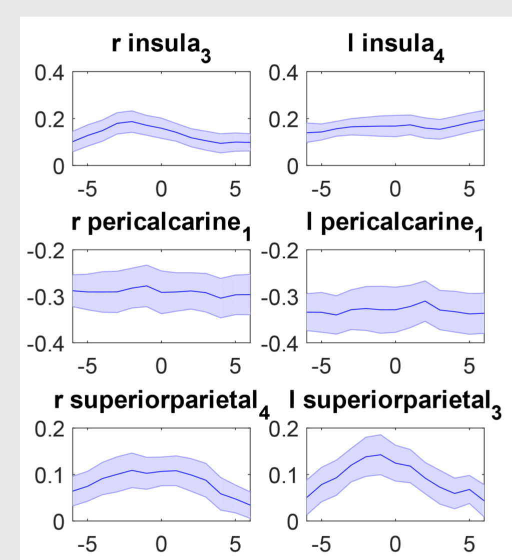


- Pupil diameter and global brain network integration demonstrate qualitatively similar but inverse time courses around exploration.
- Pupil diameter decreases prior to exploration [$F(1,18) = 14.78$, $p = .001$], rises following exploration [$F(1,18) = 10.07$, $p = .005$], and shows an overall cubic modulation in the peri-explore period [$F(1,18) = 29.48$, $p < .001$].
- Integration rises prior to exploration ($p > .05$), decreases following exploration [$F(1,18) = 5.46$, $p = .03$], with an overall quadratic trend [$F(1,18) = 4.39$, $p = .051$].

Integration by system

- Integration in the post-explore period decreased most between frontoparietal systems (ps = .013 – .036, FDR corrected) and between frontoparietal systems and the sensorimotor system (ps = .016 – .031, FDR corrected).
- *Right:* Changes in integration with the sensorimotor system post-explore. Larger spheres indicate greater decrease in integration.





Integration vs. Activation

- Areas showing activation in conjunction may show different patterns of peri-explore integration with the rest of the brain.
- Of regions selected from conjunction, only r superior parietal [$F(1,18) = 4.15$, $p = .057$], l superior parietal [$F(1,18) = 3.35$, $p = .08$], and r insula [$F(1,18) = 4.73$, $p = .04$] demonstrated evidence of (quadratic) modulation around exploration.

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