Emergence of worker and free-rider mice during foraging under risk and the burst activities in their PFC-BLA-NAc circuit

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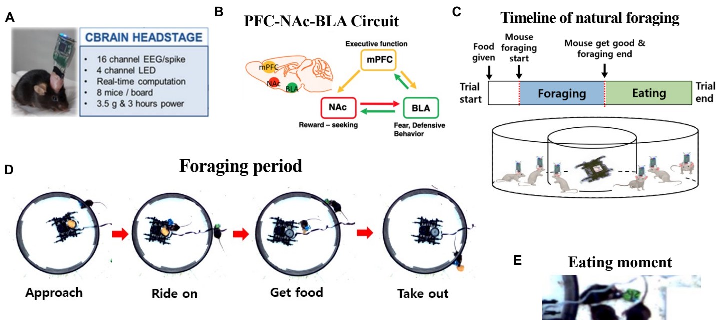
Introduction

- Mice are social animals, but little is known about whether a co-housed group of mice has a clear division of labor and, if so, how this division is established.
- Here, we used a predatory robot to create an ecological foraging paradigm in a reward-threat conflict situation, and we used a telemetry system to track brain activity in the basolateral amygdala (BLA), nucleus accumbens (NAc), and medial prefrontal cortex (mPFC) of individually tagged mice using CBRAIN (Collective Brain Research Aided by Illuminating Neural activities).
- Beta and gamma frequency are prominent brain activity in cognitive process, such as reward [1],[2], vigilance [3] and fear response [4].

Results 1. CBRAIN System & Behavior expriments

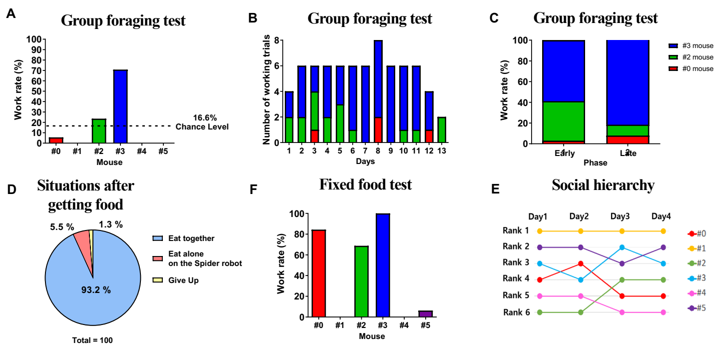


Result 1. A. CBRAIN (Collective Brain Research Aided by Illuminating Neural activities) telemetry system [5]. **B.** mPFC-BLA-NAc Circuit. **C.** Timeline of natural foraging. Food is placed on the robot by the experimenter. The foraging period is determined by the moments of the first entry to the foraging zone and the successful gathering of the food. Eating periods follow the foraging period until the food is consumed. It was repeated about six times a day with 10 min intervals. The food calorie per piece is 3.6 kcal (c.f., mouse daily intake calorie ~ 180 kcal). **D.** Snapshots of foraging behaviors. **E.** A snapshot of the eating moment. In most trials, the mice gather as soon as the worker brings the food out of the foraging zone.

Results 2. Behavior results

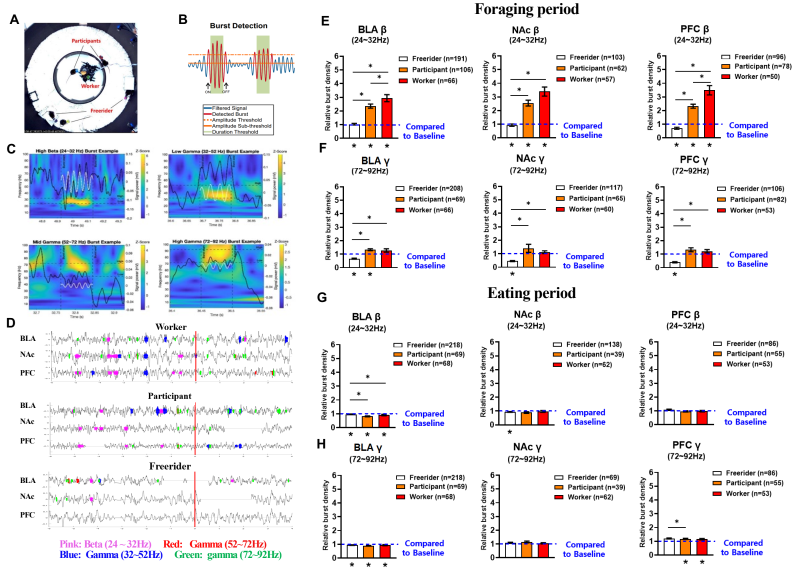
Mouse number & color

#0 Mouse #1 Mouse #2 Mouse #3 Mouse #4 Mouse #5 Mouse



Result 2. A workload imbalance grows as time goes by. A. An overall work rate of each mouse (72 trials). Note that #3 was the dominant worker, whereas #1, #4, and #5 mice never worked throughout the whole session. **B.** Daily working trials. **C.** Work rates in the early (1~6 days) versus late (7~13 days) trials. **D.** Percentage of situations that happened after foraging. Out of 72 trials, only one time, no one brought the food. There were only four times that the worker ate alone in the spider zone, and in the other 67 trials, all mice shared the food. **E.** Work rate in the fixed food case (33 trials). The food was stuck on the spider. Therefore, the mouse could not bring the food out of the zone. Participants (#2 and #5) mice worked much more frequently compared to unfixed trials. **F.** The social hierarchy of six mice (Social Hierarchy: #1>#5>#3>#2>#0>#4).

Results 3. Identification of the roles and burst density analysis



Result 3. Beta (24–32 Hz) and gamma (72–92 Hz) bursts are increased in BLA, NAc, and PFC during the foraging behavior. A. The roles of individuals were classified into one of three classes: Worker, Participant, and Free-rider. **B.** Burst detection algorithm: thresholds are produced using the mean and the standard deviation of the signal. Then bursts are singled out based on the number of peaks they contain. The minimum number of cycles for a burst was set to 3. multiplied by the standard deviation was set to 2.3. **C.** Represent of beta (24~32Hz) and gamma (32~52Hz, 52~72Hz, 72~92Hz). **D.** Representative burst activities of each role in BLA, NAc and PFC. **E-F.** Foraging period. Beta and gamma bursts were increased in Workers and Participants compared to Free-riders across brain regions. BLA and PFC beta bursts were further distinct between Workers and Participants. All cases of beta burst densities showed different distributions compared to the baseline. **G-H.** Eating period. Distributions of burst densities were largely indistinguishable between animals. For testing the difference in the distribution of burst densities, the nonparametric Kolmogorov-Smirnov test was used. Only significant (< 0.05) statistical tests are labeled. All p-values under the threshold were evenly labeled as '*'. The blue dot line represents normalisation by baseline burst density. '*' below the x-axis indicates a significant difference compared to the baseline.

Results 4. Ratio of beta to gamma as a neural correlate of act under risk

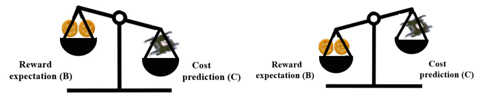
Working hypothesis

- Beta rhythm in higher regions are associated with reward expectation [1] and task certainty [2]. Therefore, we assume the top-down beta bursts represent the reward expectation, as follows

  B ~ β, where β is the beta burst rate in PFC or NAc.
- Gamma rhythm in BLA is associated with a vigilance state in fearful conditions [3]. Therefore, we assume the BLA gamma bursts represent the cost prediction as follows

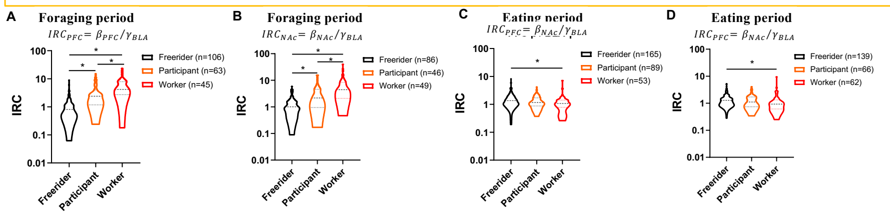
  C ~ γ, where γ is the gamma burst rate in BLA.
- In behavioral economics, the individual rationality condition, *IRC* is defined by B/C. Therefore, we defined the *IRC* for task certainty as IRC_{PFC} and *IRC* for the reward expectation as IRC_{NAc}

$$IRC_{PFC} = \alpha\frac{\beta_{PFC}}{\gamma_{BLA}}, \quad IRC_{NAc} = \alpha\frac{\beta_{NAc}}{\gamma_{BLA}}.$$



If B > C, the individual acts *If B < C, the individual does not act*

From "The logic of collective actions" by Mancur Olson (1965)



Result 4. Worker exhibits highest IRC.
A-B. IRC defined by β_{PFC}/γ_{BLA} and β_{NAc}/γ_{BLA}. were increased in the workers and the participants compared to the free-riders in foraging period. The worker exhibited a higher IRC compared to the participants and freeriders. **C-D.** IRC differed only between worker and free-riders during the eating period.
Burst density was priorly normalized using bu rst density during baseline. For testing the difference in the distribution of burst densities, the nonparametric Kolmogorov-Smirnov test was used. Only significant (< 0.05) statistical tests are labeled. All p-values under the threshold were evenly labeled as '*'. y-axis is drawn in a log scale.

Summary

- In social science, a free-rider problem is common with the public good, and the individually different participation has been mainly explained by the individual rationality condition (*IRC*). *IRC* scales individually with different expectations for the reward and the cost, respectively. Here, we quest the neural correlates of *IRC* in a group of mice.
- Here, we observed a robust emergence of working and freeriding individuals in a group of mice during foraging under a threat.
- The beta and gamma burst activities were obtained in the mPFC-BLA-NAc circuit of each mouse using a recently developed CBRAIN tool.
- Significant increases in both beta and gamma burst densities were observed in worker and participant mice during the foraging period, whereas infinitesimal changes in those values were observed in free-rider mice.
- We modeled the *IRC* by a ratio of top-down beta to bottom-up gamma, and the *IRC* of worker was significantly larger than that of participants and free-riders, suggesting the ratio of top-down beta to bottom-up gamma as a neurodynamic correlates of *IRC*.

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Reference

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