***List of Terms:***

OFC theory – cognitive map theory

OFC representations: state representations, value, cue identity

Cocaine rats: cocaine experienced

OS cues: X & Y OS cues, ABCD – Target odors

A+ vs A-, or B- vs. B+, or C+ vs C-, or D- vs D+ : use A+ vs A- and say this exemplar will be used but refers to all Target odors

Reward

Refer to OFC analyses as “representations” – define these as encompassing single unit categorization and population decoding analyses

**Aim 1.**

**Aim 2.**

**SIGNIFICANCE**

***Need to sell reversal learning here?***

Disturbances to OFC function and deficits in reversal learning, a marker of behavioral inflexibility, are both remarkably consistent features of many disorders of compulsivity in patients as well as translational animal models.

Compulsive and neurotypical behaviours do not occur in a vacuum, but instead are guided by informative cues in our environment. Activity in OFC is thought to represent the meaningful states signaled by these cues in terms of a cognitive map of state space which can be used to accurately navigate behavior to reach goals. OFC dysfunction is a common neuropathology in most disorders of compulsivity, and the behavioral inflexibility characteristic of these disorders is thought to reflect deficits in the creation and maintenance of these cognitive map representations in OFC. Key support for this comes from studies from this lab that showed showing that rats with a history of cocaine use, known to cause compulsivity, show inflexible behavior in reversal learning tasks that are accompanied by impoverished cognitive map representations in OFC. In a typical reversal learning task, subjects first learn to discriminate responding to a rewarded (A+) and non-rewarded (B-) cue, and then these cue-outcome relationships are reversed i.e. A- and B+. Rapid behavioral change in reversal learning requires a change in cognitive map to reflect the change in the relationship between cue and outcome states. However, representations of cognitive maps in OFC in reversal cannot be disentangled from simple task features such as the presence or absence of reward. That is, the reversal is signaled to the subject by a change in cue-reward associations. Further, this approach confounds time and recognition of its passage, and leaves the decision whether to even create alternative maps up to the subject. The argument is that OFC function is necessary for rapid reversal learning because it facilitates the creation, maintenance or use of these alternative maps; however, it could equally well be argued (and in fact has) that this deficit, viewed in isolation, is simply due to slower learning or deficits in response inhibition.

To resolve these issues, it is necessary to use a behavioral approach that dissociates the cue that triggers changes in the map being used from these other features and requires mapping for successful performance. One such task that still shares many of the features of reversal learning that makes it so popular is an occasion setting (OS) task. Subjects are presented with a sequence of two discrete cues, first an OS cue which indicates whether a second target cue predicts reward i.e. OS -> Target -> Reward (Figure 1). For example, target cue A is rewarded on X -> A+ trials, and non-rewarded on Y-> A- trials. This creates two cue-reward maps similar to reversal learning, except that both maps are learned from the start of the task and map switching on a trial-by-trial basis is signaled by an overt OS cue i.e. X -> {A+, B-, C+, D-} and Y -> {A-, B+, C-, D+}. Therefore, depending on whether a trial starts with X or Y, the same target cue (e.g. A) signals two distinct states (A+ or A-) in separate cognitive maps. An OS task can therefore isolate neural representations of distinct map states that are not confounded by detecting changes in reinforcement. Notably, unlike reversal learning, all cues are followed equally by reward and non-reward.

Here I will manipulate a prior history of cocaine in rats to create a model of behavioral inflexibility and OFC dysfunction in disorders of compulsivity. Using in-vivo single-cell recording in OFC during an OS task I will answer the question: Do reversal learning deficits in rats with a history of cocaine reflect impoverished cognitive map representations in OFC?

**Expt 1.**

Hypothesis: A history of cocaine use causes behavioral inflexibility in tasks like reversal learning and OS by disrupting the formation and accuracy of cognitive map representations in the OFC.

Predictions: Behavioral accuracy in an OS task will correlate with the strength and fidelity of cognitive map representations such that more distinct cognitive map representations will predict higher behavioral accuracy. Furthermore, rats with a history of cocaine use will have lower behavioral accuracy and less distinct cognitive representations in OFC compared to control rats.

Procedure: Long Evans rats (N = 16) will undergo intrajugular catheter surgery followed by a standard cocaine (n = 8) or sucrose (n = 8) control self-administration protocol for 2 weeks followed by 30 days of withdrawal. Rats will then be water deprived and given standard behavioral pretraining to become familiar with responding for odors and 10% sucrose reward in behavioral testing chambers. Next, a drivable bundle of microelectrodes will be implanted in OFC to record neural activity according to established lab procedures (ref). Following recovery, rats will be water deprived again and trained to with a novel set of cues on the OS outlined in Figure 1. On each trial, the rat will initiate cue presentation by entering and staying in the odor port, then a brief auditory cue (1000 ms) followed by an odor (500 ms) will be presented. On rewarded trials, responding to the food port below the odor port will be rewarded with a 10% sucrose solution. Correct performance will be defined as entering the food port on rewarded trials and withholding responding on non-rewarded trials. Each session will consist of 25 presentations of each trial type, presented in pseudorandom order, for a total of 200 trials. Criterion accuracy will be defined as 75% accuracy in a session. OFC activity will be recorded in all session, but neural analysis will focus on sessions with criterion accuracy.

The primary behavioral measure will be the number of sessions to reach criterion accuracy for 3 sessions in a row. Session to criterion will be compared between control and cocaine rats using a Poisson mixed-effects ANOVA model appropriate for count data.

Neural activity will be processed using methods established for analyzing activity in prior work in similar tasks (REF). It is difficult to discuss all the possible results from an electrophysiological experiment such as this, so only key analyses and predictions will be presented below. Neural analyses will focus on identifying single-unite and population level neural correlates of task features expected to reflect aspects of cognitive map representations. This will be achieved by comparing neural activity between trial conditions that require different cognitive maps i.e. differential activity during cues X and Y, as well as during cues A+ vs A-, B- vs B+, C+ vs C-, and D- vs D+. I will define the strength of unique state representations as, for example, the proportion of single units that selectively increase firing to one of these cue conditions, or the percentage accuracy of a classifier to accurately predict which cue was presented on a given trial. These measures represent two of the main methods to classify these neural correlates at the single-unit and population level.

The strength of unique neural representation will be defined, for example, If a unique subpopulation of individual neurons selectively increases

Verification of electrode placement will occur post-hoc using blinded histological processing techniques. Verification of the long-term effects of cocaine history will be confirmed by testing for sensitized (i.e. increased) locomotor activity in cocaine rats relative to sucrose rats in response to ascending doses of cocaine (7.5, 15.0, and 30.0 mg/kg cocaine injected i.p.).

Predictions.

To test the hypothesis that A history of cocaine use causes behavioral inflexibility in tasks like reversal learning and OS by disrupting the formation and accuracy of cognitive map representations in the OFC.

I will first present 3 measures of neural activity to test the hypothesis that activity in OFC reflects cognitive map representations rather than simply cue-reward value learning. I will then

Activity in OFC reflects cognitive map representations rather than simply cue-reward value learning.

The accuracy of cognitive map representations in OFC are necessary for behavioral flexibility.

A history of cocaine use causes behavioral inflexibility and disrupts the formation and accuracy of cognitive map representations in the OFC.

[3 specific neural correlates]

Given the hypothesis that activity in OFC reflects cognitive map representations rather than simply cue-reward value learning, I expect unique neural representations that discriminate between OS cues X and Y. This includes evidence that distinct subpopulations of neurons fire selectively to cue X or Y, or cues X and Y can be accurately decoded from population activity as unique trial. Cues X and Y do not differ in predicting whether the next cue is A, B, C, or D, or whether the trial will be rewarded. Therefore, differential representations of cues X and Y in OFC would not be predicted by expected outcome value or identity accounts of OFC function. However, while consistent with a cognitive map representation in OFC, differential representations of cues X and Y might simply reflect differences in the physical properties of cues X and Y. Next, to determine whether OFC represents the physical cue properties or the states within cognitive maps I will compare activity between the target cues that come after cues X and Y, that is A+ vs A-, B- vs B+, C+ vs C-, and D- vs D+. For example, when analyzing activity only during the presentation of cue A, any differences in representation must reflect information about whether a future reward is available based on whether the previous cue was X or Y. Thus, differential activity to cue A on A+ vs A- trials must reflect the unique state/position along a path within a cognitive map. Importantly, this would rule out the possibility that the OFC simply represents a cue’s physical properties or the cue’s predicted outcome value or identity. Furthermore, if OS cues which cognitive map to use to correctly interpret the meaning of the target cues, then I predict that more accurate unique representations of OS cues X and Y will predict more accurate unique representations of target cues A-D on rewarded vs non-rewarded trials. Together, these three analyses can be used to determine the strength and accuracy of the neural correlates of cognitive maps i.e. differential representation of (1) OS cues X vs Y and (2) target cues on rewarded vs non-rewarded trials (A+ vs A-, B- vs B+, C+ vs C-, D- vs D+), and (3) the correlation between them.

Given the hypothesis that the accuracy of cognitive map representations in OFC are necessary for behavioral flexibility, I predict that behavioral accuracy for an individual rat on an individual session will be predicted by the fidelity of their cognitive map representations. That is, for each of the three neural correlates described above, stronger correlates of cognitive map representations will predict higher behavioral accuracy.

I predict that cocaine experienced rats will require more sessions to learn the OS task to criterion accuracy compared to control rats. This would be consistent with the hypothesis that reversal learning deficits in cocaine experienced rats reflects a general impairment in behavioral flexibility and not simply an inability to detect that cue-reward relationships change over time. Furthermore, during neural recording sessions with criterion levels of performance, I predict that the three neural correlates of cognitive maps in OFC will be significantly lower in cocaine rats compared to control rats. These neural correlates of cognitive maps should also correlate with accuracy on a given session, similar to previous reports in reversal learning [REF]. It is also possible that cocaine rats will not show deficits behavioral flexibility in the OS task, or in the neural correlates of cognitive map representation in OFC. This would suggest that the deficits in reversal learning in cocaine experienced rats do not reflect deficits in cognitive map representations and instead reflect impairments such as value representations or inhibitory control. If this is found, the OS task conditions in this design allows for these alternative accounts to be tested.

Expt 2. Experiment 2 will test whether a novel D3-antagonist can treat the neural and behavioral deficits in behavioral flexibility caused by a history of cocaine use.

The D3 antagonist is expected to effectively treat the behavioral inflexibility in cocaine rats, that is cocaine-vehicle rats are expected to take more session to reach criterion performance than cocaine-antagonist, sucrose-vehicle, and sucrose-antagonist groups. It is unclear whether the D3-antagonist will affect control rats, and it is possible that performance will be improved or impaired in this group. Facilitation in controls might reflect a general facilitatory effect of the drug on information processing, learning, or behavioral control, whereas impaired performance might reflect a disruption of the balance between these systems. The neural analyses in Expt 1 will be used to relate the neural correlates of cognitive maps in OFC with behavioral flexibility. If the D3 antagonist effectively treats the behavioral deficits observed in cocaine experienced rats, then I predict that cognitive map representations in OFC and their relationship with behavior will match the control animals. It is also possible that treatment of the behavioral deficit does will not be reflected in normalized representations in OFC. This would suggest that a different target system is being treated by the drug. A prime neural candidate would be striatum which receives afferent projections from OFC which forms part of the common fronto-striatal neuropathology in cocaine addiction and other disorders of compulsivity.

A further prediction of a cognitive map representation within the OFC is that cues that are functionally equivalent within a cognitive map might be represented as the same state. Note that cues A and C share the same pattern of reward and non-reward after cues X and Y, as do cues B and D. If cognitive map representations in OFC reflect an abstract state space defined by, then I predict that cues A and C will have distinct representations from cues B and D, but not from each other.

To test whether these unique activity within OFC

Given the hypothesis that reversal learning deficits in cocaine experienced rats reflects impaired behavioral flexibility, I predict that cocaine rats will take more sessions than controls to reach criterion levels of behavioral accuracy.

**Bullet points of task details/email:**

* Task
* Behaviour will be within-session accuracy and sessions to reach criterion accuracy overall
  + Task is XY and AB, CD trials
    - 8 trial types, 25 of each trial type pseudo-randomly interleaved – 200 trials per session- Criterion accuracy 75% across the whole session.
    - How many session to get to 3 consecutive session with >75% accuracy
* **How will representations be analyzed?**
  + X vs Y, A+ vs A-, X->A+ vs X->B- trials [both epochs here]
  + Analysis techniques include
    - Proportion of single units that show unique selectivity between the compared conditions.
    - As measured by decoding accuracy from ensemble activity when looking at activity from either the Target Odor cue or OS cue, or both.
* Hypothesis 1: OFC activity simply represents expected cue value.
* Hypothesis 2: OFC activity simply represents expected cue identity.
* Hypothesis 3: OFC activity represents states.
* Predicition 1: Differential representations between X vs Y
  + Rules out simple value coding, and is instead consistent with identity and state representations.
* Prediction 2: Differential representations unique to each target odor cue on rewarded and non-rewarded trials e.g. A+/A-
  + Cannot simply be value representations or cue identity, can only be unique task states.
  + One alternative prediction is that unique A+/A- cues overlap with C+/C-, and also B-/B+ and D-/D+ cues. This would represent state conditions that are functional the same e.g. A and C are both rewarded after X but not after Y. This activity would represent abstract state representations which have also been found in OFC.
* Prediction 3: The fidelity of differences between X and Y should predict greater differences in representations of target odors e.g. A+ vs A-
  + Correlation of representations between OS and Target odor epochs
  + This will provide a measure of the fidelity of state representations.
* Prediction 4: The fidelity of state representations should predict behavior
  + Within session accuracy so rat by rat basis – in well trained rats i.e. sessions with >75% accuracy
* Prediction 5: Cocaine impairs these representations of differential representations of X and Y, and also A+/A- and their correlations [fidelity of state representations]
* Prediction 6: Cocaine experienced rats will require more sessions to reach criterion accuracy.
  + It is also possible that they may never reach overall accuracy comparable to controls.
  + Previously shown that some cocaine rats have recovered normal behavior, but reversal correlates correlated with behavior in impaired cocaine rats.
* Prediction 7: D3-anatagonist will improve behavioral accuracy in cocaine but not control rats.
  + Can run this as a within-subjects design in Expt 1.
  + Replication in Expt 2. But with injections during acquisition of OS.
* Prediction 8: D3-antagonist will treat any deficits in neural activity in in cocaine rats, which might be reflected as correlations in behavior
  + It is also possible that the D3-antagonist treats behavior but does not recover/treat OFC representations. This suggest that the target of action lies elsewhere. Striatum is a key alternative region.
  + If no effect is found, a simple reversal design will be used to follow up on this effect.